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NOAA Technical Memorandum NWS HYDRO-27

STORM TIDE FREQUENCY ANALYSIS FOR THE COAST OF NORTH CAROLINA, NORTH OF CAPE LOOKOUT

Francis P. Ho
Robert J. Tracey

Office of Hydrology
Silver Spring, Md.
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NWS HYDRO 14 National Weather Service River Forecast System Forecast Procedures. December, 1972. COM-73-10517)

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UNITED STATES
DEPARTMENT OF COMMERCE
Rogers C. B. Morton, Secretary

NATIONAL OCEANIC AND
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Robert M. White, Administrator

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STORM TIDE FREQUENCY ANALYSIS FOR THE COAST OF NORTH CAROLINA, NORTH OF CAPE LOOKOUT

Francis P. Ho and Robert J. Tracey
Water Management Information Division
National Weather Service, NOAA, Silver Spring, Md.

A report on work for the Federal Insurance Administration, Department of Housing and Urban Development, by the National Oceanic and Atmospheric Administration, Department of Commerce.

ABSTRACT. Storm tide height frequency distributions are developed on the coast of North Carolina, north of Cape Lookout, for the National Flood Insurance Program. Storm tides are computed from a full set of climatologically representative hurricanes using the National Weather Service numerical-dynamic storm surge model. Winter storm effects are estimated from tide gage records. Storm tide levels from all storms are shown in coastal profile between annual frequencies of 0.10 and .002. This report is intended for use in estimating actuarial risk to buildings from coastal floods and in land use management.

1. INTRODUCTION

1.1 Objective and Scope

The Federal Insurance Administration (FIA), Department of Housing and Urban Development (HUD), requested the National Oceanic and Atmospheric Administration (NOAA) to study flood levels from storm tides on the open coast of North Carolina, north of Cape Lookout (fig. 1). This includes the Atlantic Ocean coast of Carteret, Hyde, Dare, and Currituck Counties, Outer Banks of North Carolina. The assignment is limited to determining storm tide frequencies along the Atlantic Ocean coast on a common regional basis. Modifications of the storm tide levels within Pamlico Sound and in other bays are not included. These modifications have to be assessed by separate investigations, using the present study as part of the relevant information.

The tide frequencies are of still water levels that would be measured in a stilling well or tide gage house designed to exclude wave action. The destructive effects of waves on the beach front must be taken into account separately.

Storm tides in the study area are caused both by hurricanes -- which are storms of tropical origin occurring in the summer and fall months -- and by a winter type of coastal storm, commonly called a "northeaster." Both types of storms are included in the study.

1.2 Authorization

The National Flood Insurance Act of 1968, Title XIII, Public Law 90-448, enacted August 1, 1968, authorizes and directs the Secretary of Housing and Urban Development to establish and carry out a National Flood Insurance Program. The Secretary is authorized to secure the assistance of other Federal Departments on a reimbursement basis in assessing flood frequencies. Authorization for this particular study is Project Order No. 2, dated November 13, 1974, under Agreement No. IAA-H-1975 between the Federal Insurance Administration and NOAA.

1.3 Study Method

The technique used in this tide frequency analysis for the oceanic coast of North Carolina, north of Cape Lookout, is basically the same as that applied earlier to the North Carolina coast south of Cape Lookout (Ho and Tracey 1975) and in other studies (e.g., Ho 1974). The procedure is explained in detail in a separate report (Myers 1975).

First, the behavior of hurricanes along the coast both striking from the sea and passing on the inland side is assessed from past records. Factors analyzed included depression of the atmospheric pressure at the storm center below the surrounding value, forward speed and direction of motion of the storm, and distance from the storm center to the band of maximum winds. All these factors relate to a storm's potential to produce high tides.

The second step in the tide frequency analysis is to calculate the coastal tide levels that each of a number of hypothetical but representative hurricanes from various combinations of the hurricane parameters would produce. For this a dynamic calculation method is used that has been demonstrated to reproduce observed storm tides of past hurricanes within acceptable tolerances.

Finally, the computed storm surges are combined with the astronomical tide variation by using a joint probability method to obtain a frequency distribution of several classes of storms. The effect of winter coastal storms are also taken into account. These are discussed in section 5. Summing all the frequencies yields the total tide at several points on the coast. Frequency profiles along the coast are then constructed by interpolation, taking into account water-depth variations ("shoaling factor," defined in par. 4.2) and trend along the coast in climatological parameters.

These three steps are amplified in sections 3, 4, and 6 of the report, respectively.

2. SUMMARY OF HISTORICAL STORMS

This section summarizes the major hurricanes that have affected the study area since 1800 and two recent severe winter-type coastal storms. Lesser storms are omitted.

2.1 Hurricane Tracks

Selected tracks of major hurricanes affecting the study area since 1871 are shown in figures 2 and 3. These are segregated into hurricanes approaching from the southeast and southwest quadrants, respectively. Tracks of hurricanes bypassing the coast in recent years are also included.

A few hurricanes strike the Atlantic coast north of Cape Hatteras from the northeast. This type is discussed in par. 2.3. The tracks of tropical storms and hurricanes that moved from the northeast in the general region of the study area, are shown in figure 4. The information on hurricane tracks is taken from the charts of North Atlantic tropical cyclones compiled by Cry (1965). For 1964 through 1974, similar tracks are published in the Monthly Weather Review.

2.2 Historical Notes on Hurricanes

Brief notes on the history of hurricanes and damages caused by them are abstracted from published papers. Wind speeds are included to indicate the intensity of storms. Wind speeds from Weather Bureau stations from storms before 1920's have been adjusted by the instrumental corrections to anemometers developed at that time (Harrison 1963). Since that time, official wind reports include the corrections. Prior to 1940, the highest wind given for a storm was usually the "maximum velocity," an average wind speed for a five-minute period. In recent years, the highest sustained wind is an average over a one-minute period. For a complete chronology of tropical cyclones since 1586, the reader is referred to the publication on "North Carolina Hurricanes" (Hardy and Carney 1962).

September 4, 1815

A major hurricane cut across extreme eastern North Carolina in early September 1815. This hurricane moved inland on the morning of September 4, passing close to New Bern, N. C., on the Neuse River and recurved northeastward. At Beaufort, N. C., the tide flowed 4 ft higher than ever known. Every one of the more than 20 vessels at Ocracoke Inlet, along the Outer Banks of North Carolina, was driven ashore by the shifting gale. In New Bern, the tide was one foot higher than in any storm since 1795 and reached an elevation of nearly 12 ft above common high-water mark (Ludlum 1963).

June 3-4, 1825

This early season tropical cyclone swept up the Atlantic coast with reports of major damage all the way from Florida to New York City. Very high winds, which lasted 30 hrs., were reported by the post surgeon of Fort Johnston at Cape Fear, N.C. Along the Outer Banks of North Carolina the hurricane lashed at shipping settlements. Near Ocracoke Inlet, 25 vessels were driven ashore. A press dispatch from Adam's Creek, N.C., near Cape Lookout reported very heavy losses with crops destroyed and cattle drowned as the storm tide rose 14 ft above low water. At New Bern, the tide rose 6 ft and considerable damages near the water front were reported (Ludlum 1963).

August 25, 1827

This hurricane was traced to its origin in the Windward Islands on August 17. It struck the coast between Cape Fear and Cape Hatteras on August 25. Ludlum (1963) gives some descriptive accounts of the storm tides along this stretch of the coast: "The towns of New Bern and Washington, both heads of navigation for tidal rivers emptying into Pamlico Sound, suffered severely from high tides, and such high waters, too, are always caused by wind with an easterly component. At Washington the tide was 12 to 15 ft above ordinary tides and houses on Water Street found the river 5 to 6 ft deep in their first floor during the height of the storm tide. At New Bern all communication for a while was by canoe. Near Cape Hatteras two New York-to-North Carolina packets were driven ashore and smashed to pieces by the tremendous breakers. The new Cape Hatteras Lightship off Ocracoke Inlet broke loose and piled up on the south side of Ocracoke Island."

July 12-15, 1842

A very destructive hurricane swept the entire North Carolina coast, apparently most severe in the Ocracoke - Portsmouth, N.C., area. This storm was reported to have been the most violent experienced at Ocracoke Bar for 80 years (another great hurricane in 1761 changed much of the coast-line of the Outer Banks and cut through the New Inlet near Wilmington, N.C.). The damage along the Outer Banks was immense. The entire village on Portsmouth Island near Ocracoke Inlet, with the exception of one building, was wrecked. A store at the settlement was blown down and floated away at the height of the storm. Fourteen vessels went aground on the ocean beach near Ocracoke Inlet and fourteen more on the inside beaches. Two unknown vessels were dashed to pieces in the breakers on Diamond Shoals. A number of dead horses and cattle were seen drifted down the Sound after the storm was over (Ludlum 1963).

September 7-8, 1846

This hurricane apparently approaching slowly from the south opened up two new inlets of major commercial importance across the Outer Banks. To the south of Cape Hatteras, a new Hatteras Inlet between Ocracoke and Hatteras Islands provided a new entrance into Pamlico Sound. To the north, Oregon Inlet (named after the first ship to pass through) split Bodie Island below Nags Head for a more direct route to Albemarle Sound ports. The hurricane caught 20 ships at Ocracoke Inlet and drove all but two of them ashore or out to sea. The small community of Hatteras just south of the Cape had all but six houses flattened by the storm. At Nags Head the tide rose about 9 ft higher than common tide (Ludlum 1963).

October 23, 1878

This hurricane moved northward across Cuba, skirted the east coast of Florida and moved inland between Wilmington and Morehead City, N.C., on October 23rd. It struck the Outer Banks with full hurricane force, with maximum winds of 77 mph recorded at Cape Lookout and 63 mph at Portsmouth. The steamer City of Houston was lost on Frying Pan Shoals; a great many ships were damaged or lost in the storm all along the Atlantic coast (Hardy and Carney 1962).

August 18, 1879

A severe hurricane moved inland near Wilmington on the 18th and back out to sea near Norfolk with highest winds reported at Cape Lookout. The anemometer cups at Cape Lookout were blown away and the wind was afterward estimated to have reached 127 mph. Anemometers were also destroyed at Hatteras, Fort Macon, Kitty Hawk, Portsmouth, N.C., and Cape Henry, Va., with speeds estimated at 100 mph or more. A ship report indicated waves forty feet from trough to crest. This storm was most destructive in the Morehead City - Beaufort, N.C., area where two hotels were destroyed and 1,000 ft of railroad track torn up. All the wharves were washed away and the chimneys of most houses were blown away. On the Outer Banks, the storm caused great damage at Diamond City, which was near Cape Lookout (Hardy and Carney 1962).

August 17-18, 1899

One of the most severe hurricanes on record for the Hatteras area moved slowly northward across the Outer Banks during August 17-18. By early morning of the 17th, the wind was blowing from the northeast at 54 mph at Hatteras; it had reached 71 mph at 1:00 p.m. with extreme velocities of 90 to 105 mph. The anemometer then blew away; stronger winds probably occurred. Hatteras reported a barometer reading of 968.9 mb (28.61 in) at 8:00 p.m. of the same day (U. S. Weather Bureau 1899). The Weather Bureau observer at Hatteras reported that "the entire island" was covered with water to a depth of 4 to 10 ft. There were not more than four houses in which the tide did not rise to a depth of 1 to 4 ft. All fishing piers and equipment were destroyed; all bridges were swept away; a great proportion of the homes on the island were damaged. There was much destruction at Diamond City, N.C. Flooding of much of the coastal areas and strong winds and heavy rains inland as far as Raleigh did great damage to crops (Hardy and Carney 1962).

July 31, 1908

This storm had its inception as a tropical storm off the east coast of Florida. It then moved to the east-northeast, did a complete "loop" and became a hurricane as it moved northeastward off the coasts of Georgia and the Carolinas. It moved inland near Cape Lookout on July 31 then across Pamlico Sound, continuing its northeastward movement. Highest reported wind was 46 mph at Hatteras, but the storm piled up considerable water on the North Carolina coast south of Hatteras. This combined with torrential downpours (10.73 inches in 72 hours at New Bern and 9 inches at Kinston) caused much flooding in the eastern counties. Damage was "immense," but no injuries or fatalities were recorded. At New Bern, this was "the worst storm in history" (Hardy and Carney 1962; Corps of Engineers, Wilmington, N.C. 1961; and Sugg, et al., 1971).

September 16, 1933

This hurricane formed east of the Leeward Islands, moved northwest and then northward, increasing in intensity and striking the coast a little west of Hatteras about 8 a.m. on the 16th. Maximum wind speed at Hatteras was estimated at 76 mph because a portion of the anemometer was blown away. Winds were estimated up to 125 mph in New Bern and Beaufort. Minimum barometric pressure at Hatteras was 957 mb. Damage was heavy from a short distance south of New Bern to the Virginia line. It was reported that hardly a building was left standing in several coastal towns. High winds, waves, and piling up of water in Pamlico and Albemarle Sounds caused 21 deaths. Wind and water did great damage at New Bern where water was reported to reach "a height of 3 to 4 ft" (Hardy and Carney 1962). An estimated high tide of 7.0 ft MSL occurred at Ocracoke, N.C. (Corps of Engineers, Wilmington, N.C. 1963).

September 18, 1936

This hurricane was one of the most severe hurricanes of record at Hatteras. Maximum winds of 80 mph from the northwest were reported at Hatteras and 90 mph at Manteo, N.C. As the hurricane approached Hatteras it began recurving northward and the storm center passed close to the station on the coast. The highway from Currituck, N.C., to Norfolk, Va., was washed out. About 35 ft of beach was cut away at Nags Head, N.C. Tides were very high at Manteo and Hatteras (Hardy and Carney 1962). A high tide of 6.0 ft MSL was reported at Hatteras and an estimated 6.3 ft MSL at Ocracoke, N.C. (Corps of Engineers, Wilmington, N.C. 1963).

September 14, 1944

The "Great Atlantic Hurricane" of September 1944 caused destruction to 900 miles of the Atlantic coast from Hatteras northward. The center of the hurricane passed a short distance to the east of Hatteras with estimated maximum winds of 110 mph. At Hatteras a lowest barometric pressure of 947.2 mb (27.97 in) was recorded, the lowest pressure reading on record at the station. Cape Henry, Va., reported maximum winds of 134 mph with gusts estimated at 150 mph (Sumner 1944). There was heavy damage in Elizabeth City, N.C., and the Nags Head area. The storm was very severe and caused considerable property damage on Ocracoke Island. Local residents reported the highest tide on record at Ocracoke Village, 7.5 ft MSL (Corps of Engineers, Wilmington, N.C. 1963). A highest tide of 7.0 ft above mean low water (6.0 ft MSL) was reported by the U. S. Weather Bureau at Hatteras, N.C. (Sumner 1944).

August 12, 1955 - Connie

Hurricane Connie entered the North Carolina coast close to Cape Lookout about 8:30 a.m. on August 12. The prolonged pounding of high waves against the coast caused tremendous beach erosion estimated to have been worse than that caused by Hazel in 1954. Tides of about 4.0 ft MSL were reported at Ocracoke and Hatteras, N.C. (Corps of Engineers, Wilmington, N.C. 1963), while water in the sounds and near the mouths of rivers were 5 to 7 ft MSL (Harris 1963). At Fort Macon, N.C., winds of 75 mph with peak gusts of 100 mph and lowest pressure of 962 mb were reported. The storm also brought torrential rains with the maximum, ranging around 12 inches within 48 hr falling near Morehead City. Total damage throughout the state was estimated at $50 million (Hardy and Carney 1962).

September 19, 1955 - Ione

Hurricane Ione, moving from the south, crossed the North Carolina coast near Salter Path, about 10 mi west of Morehead City, about 5 a.m. on September 19. It then slowly curved to the northeast, passing out to sea near the Virginia stateline early on September 20. When Ione entered North Carolina, highest winds were a little over 100 mph in gusts. The highest recorded wind speed was 75 mph gusting to 107 mph at Cherry Point. Minimum barometric pressure over North Carolina was 960 mb. Heavy rains accompanied Ione. At the same time, prolonged easterly winds drove tide water onto the beaches and into the sounds and their estuaries to a height of 3 to 10 ft above normal. The result was inundation of the greatest area of eastern North Carolina ever known to have been flooded. At New Bern, the depth of water was the greatest of record, being about 10.5 ft above mean low water, with 40 city blocks flooded. Several hundred homes were washed away and thousands were flooded by water with depths ranging up to 4 ft (Hardy and Carney 1962). A high tide of 7.2 ft MSL was reported at Atlantic Beach, N.C. (Harris 1963). High tides of 5.7 and 3.8 ft MSL at Ocracoke and Hatteras, N.C., respectively, were reported by the Corps of Engineers (Corps of Engineers, Wilmington, N.C. 1963).

September 27, 1958 - Helene

Hurricane Helene was one of the most powerful storms of recent history and, fortunately for North Carolina, the storm center moved up the coast staying well out at sea, on September 26-27. Even so, the highest winds of record were recorded at Wilmington, with peak gusts of 135 mph and fastest mile 85 mph. The lowest reported central pressure was 932 mb at a point south-southeast of Cape Fear early on the morning of the 27th (aircraft reconnaissance). There was some beach erosion due to seas and tides but this was minimized by the passage of the storm at time of low astronomical tide. The highest tides on ocean beaches were estimated at 3 to 5 ft above normal. Tides were higher on the southern edge of Pamlico Sound, where a sudden rise following the wind shift as the center passed brought the tides to 7 or 8 ft above normal (Hardy and Carney 1962). At Ocracoke, N.C., local residents stated it was the most severe storm since 1944. Water covered most of the island and swept into about 25 homes in the village. The northern end of the island was breached at six different locations during the storm. Over 2.5 mi of state highway steel-mat pavement was washed out, and approximately 12 mi of National Park Service sand fence located near the ocean shore was destroyed. High-water mark of 5.5 ft MSL was reported by local residents in the village of Ocracoke. A high tide of 5.1 ft MSL was recorded at Hatteras, N.C. (Corps of Engineers, Wilmington, N.C. 1963).

September 11, 1960 - Donna

Hurricane Donna passed inland over the North Carolina coast between Wilmington and Morehead City on September 11. The center of the storm passed a few miles east of Wrightsville Beach, although Wilmington and Wrightsville Beach were in the "eye" for about an hour. Lowest barometric pressure at Wilmington was 962 mb. Tides of 6 to 8 ft above normal combined with high winds caused severe damage at many points. Maximum winds were of hurricane force with Wilmington reporting a peak gust of 97 mph. The storm center moved northward along a path slightly east of a line from Wilmington to Norfolk during the night of the 11th. Coastal communities suffered heavy structural damage from Wilmington to Nags Head, with considerable beach erosion. Wind gusts were in excess of 100 mph and tides were 4 to 8 ft above normal (Hardy and Carney 1962). High tides of 10.6 ft MSL were reported at Atlantic Beach, N.C., and 4 to 6 ft MSL in the sounds and near the mouths of rivers. Tides of 3 to 4 ft MSL were reported on the Outer Banks near Hatteras (Harris 1963).

September 30 - October 1, 1971 - Ginger

Ginger will be noted chiefly for its longevity and circuitous track. This storm was tracked for 31 days during 20 of which it was a hurricane. On September 27, Ginger moved northwestward and set a steady course toward the North Carolina coast. Its center crossed the coast near Morehead City on the evening of September 30 with maximum sustained winds of 75 mph and minimum central pressure of 993 mb. Total damage caused by the storm in North Carolina is estimated at $10 million. Tides on Pamlico Sound were 4-7 ft above normal. At Washington, Aurora, New Bern, and Cherry Point, N.C., tides were 6 ft above normal. On the ocean beaches at Hatteras, tides were 2-3 ft above normal (Simpson and Hope 1972).

2.3 Winter Coastal Storms

The study area is exposed to winter coastal storms, especially from Cape Hatteras northward. Strong winds from the northeast quadrant are experienced over long reaches of coast, hence the familiar name "northeaster." These winds are part of a counter-clockwise cyclonic atmospheric circulation about a center of atmospheric pressure, at sea. The area of proximity of warm gulf stream water off the North Carolina Banks is a favored region for the development and intensification of such storms. They are most common and most severe during winter and spring months. Many of these storms move rapidly to the north and northeast but under favorable conditions of the general atmospheric circulation they can stall and intensify with little forward motion for a couple of days.

These storms raise the tide (still water level that would be observed in a tide gage house if one existed) but not as high as in the more severe hurricanes. The aspect of a northeaster most damaging to the exposed beaches of the Outer Banks is the persistence of pounding waves, developed by wind blowing toward the coast over long stretches of ocean. The extent of these damages may be illustrated by citing reports on recent coastal storms of March 7, 1962 and February 17, 1973.

March 7, 1962

The second worst northeaster of the present generation was on March 7, 1962, locally known as the "Ash Wednesday storm." The effects were similar to the 1973 storm described below, though there was less destruction to buildings (in the study area) because the several communities were less built up at the time. There was considerable damage to private property along the shore in the Nags Head, Kill Devil Hills area (Corps of Engineers 1966). The storm opened a new inlet just north of Buxton, N.C. This was filled and closed at considerable expense by dredges several months later (Corps of Engineers 1963). On some parts of the Delmarva Peninsula, to the north of the study area, this was the most damaging of all coastal storms, including hurricanes, of record to date.

February 17, 1973

The most damaging winter coastal storm of the present generation was on February 17, 1973. The following newspaper quote succintly describes the storm:

"North Carolina's land mass is smaller by several hundred acres this week as a result of a severe coastal storm which gnawed away at beaches from Corolla to Cape Fear.

"During the two days following a freak storm that frosted the state's eastern lowlands with up to 15 inches of snow, savage 56-knot winds and powerful 40-foot waves hauled tons of sand from the shore.

"The wind-whipped sea toppled large buildings in resort communities on the Outer Banks, nearly bisected at least two offshore islands, ripped up highways, filled roadbeds with sand and carved away large chunks of sandy beach.

"The worst of the storm's fury was directed at Buxton, Kitty Hawk and Nags Head, but severe erosion and some property damage occurred at the more southerly resort communities of Wrightsville Beach, Carolina Beach and Topsail Beach." (Raleigh News and Observer February 19, 1973).

A typical description of local damage, from the same source, is "At Kitty Hawk four beach cottages were washed away, nine were toppled by the waves but left partially standing, 12 others received structural damage from the pounding surf and dozens of others are left standing so near the encroaching sea that another storm would undermine them."

3. CLIMATOLOGY OF HURRICANE CHARACTERISTICS

This section describes important characteristics of hurricane parameters that are needed for calculating tide levels on the coast. Basic parameters of hurricanes affecting the U. S. coast, including central pressure, radius of maximum winds, speed of forward motion, and direction of forward motion, all factors affecting storm-tide producing capability, were published in 1959 (Graham and Nunn 1959). This compendium of hurricane characteritics has been updated through 1973 and adapted to the needs of the Flood Insurance Program, including specification of probability distributions of the individual parameters. These data are published in a separate report (Ho, Schwerdt, and Goodyear 1975) hereafter referred to as the Climatology Report, and are the primary data source on hurricanes for the present study. These data are used directly for the portion of the study area south of Cape Hatteras, with certain refinements in hurricane track count described later. North of Cape Hatteras the methods of the Climatology Report were extended by certain additional analyses, described in par. 3.2.

3.1 The General Method - South of Cape Hatteras

For the purpose of determing parameter probabilities, in the Climatology Report hurricanes and tropical storms are grouped into three classes, those which landfall on the coast, those which bypass alongshore with the center remaining at sea, and those which exit the coast (after an earlier entry of the coast elsewhere). In this study, south of Cape Hatteras, the first two classes are used. Exiting storms are not significant there.

3.1.1 Probability Distribution of Hurricane Intensity

Storm surge magnitude varies approximately with the strength of the wind that is putting stress on the water surface, other factors being constant. An index of this wind stress in hurricanes is the intensity of the storm as measured by the depression of the storm's central pressure below representative peripheral pressure (D). The assessment of probability distributions of this parameter for landfalling and alongshore storms is described in the Climatology Report.

3.1.2 Probability Distribution of Radius of Maximum Winds

In all hurricanes, proceeding from the storm center outward, winds increase from low values at the center of the eye to their most intense velocity just beyond the edge of the eye, then decrease gradually. The average distance from the storm center to the circle of maximum wind speed is called the radius of maximum winds (R) and is adopted as a convenient single number to be used as an index of the size or lateral extent of the hurricane, a factor which affects the surge profile along the coast. R values are taken from the Climatology Report and applied to both classes of storms.

3.1.3 Probability Distributions of Speed and Direction of Forward Motion

The speed (T) and direction (θ) of forward motion of hurricanes also affect surge height. The height of the surge on the coast increases with increasing storm speed up to a forward speed higher than that of any hurricane in the study area. Thus, the occasional fast-moving storms, especially if they are large and moving directly toward the coast, pose the greatest hazard. Probability distributions of forward speed for the landfalling and alongshore storms are given in the Climatology Report previously cited. The probability distribution of direction of forward motion for landfalling hurricanes and tropical storms is also discussed in the Climatology Report.

3.1.4 Frequency of Hurricane Tracks

The overall frequency of hurricane occurrences is basic to calculating the resulting tide frequencies. The frequency with which hurricane and tropical storms have entered or exited the coast and have moved approximately parallel to the coast at sea ("alongshore") based on 103 years of data smoothed along the coast is given in the Climatology Report. These counts are used in this study, except that further analysis was made to the original data to take into account in greater detail the influences of seaward extensions of the land of the turning of the coastal orientation near Cape Hatteras. Additional counts of alongshore storms immediately opposite Cape Hatteras, Ocracoke and Cape Lookout were made from Cry's (1965) annual track charts to secure more detail in the vicinity of these features. The frequency distribution of landfalling storms in the study area is discussed in par. 3.2.4.

3.2 Special Considerations North of Cape Hatteras

Landfalling hurricanes and tropical storms in the study area north of Cape Hatteras are further classified to deal with the joint probability questions referred to in Chapter 6 of the Climatology Report, and to take into account the effects on the coast of storms passing inland to the coast. The latter are not covered in detail in the Climatology Report.

3.2.1 Conditional Probability Question

It will be explained in section 6 that assessing the probability of a certain combination of hurricane parameters involves multiplying together the probabilities of each of the parameters, on a scale of 0 to 1.0, provided the distributions of the several parameters are independent in the statistical sense (Chapter 6 of the Climatology Report). If the distributions for any two parameters are not essentially independent, then this must be recognized by either using conditional probabilities or by segregating the possible hurricane events into subsamples. An example of the subsample segregation in the Climatology Report is the division of hurricanes into "landfalling" and "alongshore." Separate forward speed distributions are then determined for each subsample.

North of Cape Hatteras we must deal with the correlation between hurricane intensity and the direction of storm motion relative to the coast. This is alluded to in paragraph 6.3 of the Climatology Report as an example of conditional probability questions that may be expected in various regions, but specific data are not developed. Hurricanes landfalling from the southeast quadrant cover the full range of intensities from very severe to weak. From time to time in this region a hurricane meanders and strikes the coast from the northeast quadrant. These storms are either of a weaker category initially or, if originally intense, have been weakened by transit over cold water and other effects. The speed distribution for these storms is also different from those moving from the southeast quadrant. These storms all move at less than 15 kt. A separation for all parameters, including track frequency, was made between landfalling storms from the SE and NE quadrants north of Cape Hatteras. This is described in the next several paragraphs.

3.2.2 Parameters for Landfalling Hurricanes from Northeast Quadrant

To provide the hurricane parameter data needed for this part of the study, a special analysis was made of hurricanes and tropical storms landfalling from the northeast quadrant. For this the original data from the Climatology Report were used plus that for other hurricanes and tropical storms farther at sea to expand the sample. Hurricanes and tropical storms moving from a northeasterly direction within an area west of 70°W and north of 30°N were examined. The speeds of forward motion were measured from Cry's storm tracks, and a probability distribution formed. A sample of eight central pressure values from the most recent storms were used to derive a probability curve for this parameter. There is insufficient information to determine a separate frequency distribution of radius of maximum winds for this class of storms, but there is no reason to think that it would differ much from the distribution for all hurricanes at this latitude. The R distribution as given in the Climatology Report is therefore adopted.

3.2.3 Parameters for Landfalling Hurricanes from Southeast Quadrant

To obtain the probability distribution of central pressure for the storms landfalling from the southeast quadrant, the probabilities for northeast quadrant hurricanes and tropical storms were subtracted from the overall probability for all landfalling hurricanes in the Climatology Report, weighted by their percentage of occurrence. The probability distribution thus obtained by subtraction was also checked against a direct sample of storm data. The resultant distribution for the SE storms differs only slightly from that of all landfalling storms. This is illustrated in figure 5 (curves a and d). Speed of forward motion probabilities were evaluated in a similar manner. Figure 6 shows the resulting comparative probability distributions of forward speed. The probability distribution of radius of maximum winds from the Climatology Report is adopted for the southeast quadrant hurricanes.

3.2.4 Landfalling Track Frequency

The frequency of landfalling storms from the northeast and southeast quadrants are not given in the Climatology Report separately. The segregation of landfalling hurricanes and tropical storms into quadrant of approach calls for a discontinuity at Cape Hatteras in the overall landfalling frequency. The frequency of storms landfalling from the sector 91° - 160° is approximately the same immediately north and south of the Cape. But landfalls from the other possible directions -- 161° - 240° south of the Cape and from the northeast quadrant north of the Cape--are not of equal frequency. Thus there is a difference in the total landfall frequency. The overall storm landfalling frequency, a factor in storm tide frequency computation, smoothed along the coast by weighted moving averages in the Climatology Report, is adjusted to define this discontinuity. A track count of storms from the northeast quadrant and the 91° - 160° sector crossing overlapping two-degree latitude and longitude squares was examined separately. The sum of these frequencies was checked against the frequencies of all landfalling storms. Figure 7 depicts the resulting frequencies with which hurricanes and tropical storms entered the coast from different sectors both north and south of the Cape. The plotted points (circled dots) show the frequencies of direct track counts at 50-n.mi. intervals as given in the Climatology Report. SE-quadrant parameters (par. 3.2.3) were applied to the 91° - 160° sector storms.

3.2.5 Hurricanes Passing Inland

Because of the North Carolina coastal configurations and the propensity of hurricanes to recurve and move northward in this region, many hurricanes landfall on the coast south of Cape Hatteras and then move on a course approximately parallel to the coast north of the Cape. The tracks of some of these are shown in figures 2 and 3. Hurricanes and tropical storms which bypassed within 100 n.mi. inland of the coast were assessed by separate counts of storm tracks crossing 35°N and the N.C.-Va. border on the same 103 years of track charts. The cumulative track counts along each line were plotted and a smooth curve fitted by eye to the data on each of these frequency plots.

The accumulated frequencies for storms bypassing inland for Wright Monument, N.C., obtained by interpolation is shown in figure 8 (together with alongshore frequency at sea). A similar analysis was made for Salvo, N.C.

The central pressure for inland storms was estimated by applying an average empirically-derived filling rate after the storm center landfalls.

Malkin (1959) studied the filling rates of 11 hurricanes moving inland in the southern and eastern United States, with the Florida Peninsula excluded, and constructed an empirical average curve of central pressure vs. time over land (his figure 1). An exponential decay of the form

$$D_i = D_c e^{\alpha t} \tag{1}$$

where D_i is the pressure deficit (surrounding pressure minus central pressure) of the storm inland, D_c the central pressure deficit at the coast, t time inland, and α the fractional change in D in one time unit, fits these data rather well. Expanding in a series and dropping higher order terms

$$D_i = D_c (e^{\alpha})^t = D_c (1 + \alpha)^t. \tag{2}$$

Substitute LL/T = t, where LL is distance inland and T average speed,

$$D_i = D_c\ (1 + \alpha)^{LL/T}. \tag{3}$$

A value of $\alpha = -.04$ per hour provides a good fit of eq. (3) to Malkin's curve and was adopted.

Representative D_i's for storms passing inland of the coastal stations north of Cape Hatteras were obtained by making the following approximations and substituting in (3). (a) Lay out tracks paralleling the coast; for LL use distance from coastal entry point to latitude of station as shown in figure 9. This is done separately for various distances, L, inland from the coast. (b) For T use the median speed for landfalling storms at the latitude of the station, from the Climatology Report. (c) For D_c use pressure depression values from the Climatology Report for landfalling storms at the latitude of the station.

Figure 5 shows the three derived probability distribution curves of central pressure of hurricanes and tropical storms for Wright Monument, N.C. Curve d from the Climatology Report is shown for comparison. (Combining a and b, weighted by frequency, yields d.) It will be noted that the diagram shows only the fraction of all storms with intensities below certain levels and makes no reference to frequency in terms of events per year.

The speed of forward motion for inland storms was measured from storm tracks crossing the N.C.-Va. border within 100 n.mi. of the coast, and a probability distribution of this parameter was formed. For R there are insufficient data for a direct analysis. R may expand faster for storms over land than at sea but this has not been verified. In any event, for this study the contribution of inland storms to coastal tide frequencies is small and does not demand attempts to refine R probabilities. The distribution of R in the Climatology Report is used for inland storms.

3.2.6 Exiting Hurricanes

The frequency with which hurricanes and tropical storms exited the coast is given in the Climatology Report. Other parameters are adapted from those for the landfalling and inland categories. Approximating the parameters and grouping into fewer class intervals suffices for these computations as exiting storms produce lower storm tides, and, as it turns out, make an almost negligible contribution to the overall storm tide frequencies (e.g., curve d, figure 13).

3.2.7 Alongshore Hurricanes

Alongshore hurricane parameters are given in the Climatology Report. Intense hurricanes belong in this group. The probability distribution of central pressure used in the computations is the same as that of the SE landfalling storms. This class of hurricanes has a higher percentage of fast-moving storms than those of landfalling and exiting categories.

4. HURRICANE SURGE

4.1 Surge Model

The National Weather Service has developed a two-dimensional numerical dynamic surge model for calculating the water levels induced by hurricanes on the continental shelf (Jelesnianski 1967, 1972, and 1974). The objective of this work was to develop a tool to forecast open coast surges when hurricanes were approaching. The model has become the backbone of NOAA's tide-frequency studies for the flood insurance program. The development of the model is described by Jelesnianski in the 1967 paper and operational applicatons (designated as SPLASH I and II) in the others. Both limitations and verification of the model are described in the references. Replication of surge profiles produced by past hurricanes agree well with observed storm tides and high-water marks adjusted to exclude astronomical tide. The model computes the surge, the difference between the local storm-induced level and the normal water levels for the area. Thus, the computed storm surge must be added to the predicted astronomical tide.

Inputs to a computer surge calculation are hurricane central pressure deficit, radius of maximum winds, storm direction of motion and forward speed, and ocean depth at a series of grid points. The hurricane climatology just described is oriented toward providing these parameters. The computer program generates the needed moving sea-level pressure field and moving wind field from the basic parameters by predetermined relations which are part of the model.

The SPLASH I version is limited to storms moving forward at constant velocity and intensity toward a specified landfall point while SPLASH II has been expanded to accommodate storms with generalized motions of not too great complexity. Also, storm strength and size are allowed to vary in a continuous monotonic manner with time. In the present study, SPLASH II was used to compute surges generated by alongshore and inland hurricanes. Since SPLASH I and II give the same result for landfalling hurricanes with a constant velocity and intensity, landfalling hurricane surges were computed by the SPLASH I program as it is slightly simpler to use.

4.2 Shoaling Factor

The capacity of a hurricane of given characteristics to produce a coastal surge depends on the profile of water depth. The shallower the coastal water the higher the surge. This variation along the East coast is depicted in a report by Barrientos and Chen (1975, figure 3b) as the ratio of the surge that would be produced locally at each coastal point by a standardized hurricane to the surge from the same hurricane moving over a continental shelf of average or standard slope. This ratio is called the shoaling factor, and is generated by computing surges by the model that has been described at the various coastal points and over the "standard basin" and taking ratios of the peak surges. The North Carolina portion of this diagram is reproduced in figure 10. The shoaling factor is implicit in calculations of hurricane surge by the model at selected coastal points, since the sloping depths of the continental shelf are introduced by input data to the calculation. The shoaling factor is specified at 4-mi intervals in the SPLASH program (relative to the value at the center of the "basin") and is a primary guide to interpolating between coastal computation points. The shoaling factor curve of figure 9 reveals that a minimum factor is reached near Ocracoke Inlet and comparatively higher factors appear to the north of Salvo, N.C. The top curve (for R=26 n.mi.) is applied to hurricanes with R>19.5 n.mi. in this study and the lower curve to smaller hurricanes.

5. WINTER COASTAL STORM TIDES

5.1 Evaluation of Northeaster Tide Levels in Study Area

Some of the 10-yr return period magnitude (10% probability per year) storm tides in this study area are caused by northeasters, as will be shown later in the report. At the 100-yr return period magnitude (1% chance of being exceeded in any year) the activating storms are hurricanes and the additional contribution by northeasters is negligible by comparison. For purposes of this study, the northeaster contribution to storm-tide frequencies may be evaluated with sufficient precision by direct analysis of long period tide gage records and interpolation for frequencies at selected points along the coast.

5.2 Analysis of Tide Gage Records

There are no permanent long period tide gage records within the study area itself. We go to the nearest National Ocean Survey Reference Stations to the north and south, with more than 30 yr of record. These are at Hampton Roads, Va., (45 yr) and Wilmington, N.C. (37 yr). To focus on northeasters and exclude hurricanes, at each station the maximum tide was abstracted for each October through May season, with an additional check of weather maps to exclude any hurricanes which might occur in early October. These data series were treated as "annual series" and frequency curves fitted. The plot for Hampton Roads is shown in figure 11. A frequency curve was fitted by eye using two curves from standard statistical distributions as guides. The 100-yr northeaster tide level from the eye-fitted curve is 7.0 ft MSL. At Wilmington, the annual maxima conform to the two standard statistical distributions and either yields a 100-yr northeaster tide level of 5.0 ft MSL. The maximum of record at Wilmington is 4.7 ft MSL in 1972. All of the data were adjusted for sea-level trends to 1970 conditions by using factors from Hicks and Crosby (1974).

Estimated northeaster tide frequency curves for selected points within the study area were constructed by assuming that Wilmington values are lower than on the open coast, then interpolating approximately linearly along the coast. Reported highest storm tides are an additional guide. These include 7.6 ft MSL at Norfolk, Va., 6.5 ft at Cape Hatteras, 5.6 ft at Wrightsville Beach, N.C., (Cooperman and Rosendel 1962), and 8 ft MSL at Nags Head (Corps of Engineers 1966). A subjective evaluation was required of relative effects on the eastward-facing coast north of Cape Hatteras, and the southeastward-facing coast south of the Cape, from sustained northeast or eastnortheast winds. Several investigations (e.g., Pore 1964) indicate that northeaster tide levels are at least as well correlated with the alongshore component of the wind as with the onshore component. This justifies an approximately linear interpolation in spite of the change in direction of the coast. The estimated Wright Monument and Ocracoke Inlet curves are shown in figures 13 and 14, respectively.

6. TIDE FREQUENCY ANALYSIS BY JOINT PROBABILITY METHOD

6.1 The Joint Probability Method

The first step in the joint probability method is to define the probability distributions of the several hurricane parameters. This has been described in Section 3. Each distribution is divided into class intervals, and the midpoint values are read out for each class interval. The parameters derived in this way and used in the subsequent computations are listed in tables 1 to 5 for the coast at the N.C.-Va., border, Wright Monument, Salvo, Ocracoke Inlet, and Cape Lookout, N.C., respectively. As indicated in Section 3, many of these parameter values are taken directly from the Climatology Report; others were derived in the course of this study. Each combination of D, R, T, and θ represents a climatologically possible landfalling hurricane or tropical storm. For example, the parameters for landfalling hurricanes and tropical storms in table 4 (8D's, 2 or 3 R's 6 T's, and 3 θ's) define 396 different storms which in the aggregate represent the climatological possibilities in the vicinity. The probability (fraction of all hurricanes) of each of these is obtained by multiplying the respective parameter probabilities in the table. The sum of the probabilities of the 396 hurricanes, of course, equals 1.0. The parameters in the table are considered independent in the statistical sense except that the three R's are not the same for all pressure depression categories, smaller values being used with the more intense pressure depressions in line with the discussion in the Climatology Report and as shown in the table.

As the second step, calculations are made with the SPLASH computer program of the coastal surge profile for each landfalling hurricane. Many of the surge profiles are obtained by adjustment of other profiles rather than by complete surge calculations. Each storm is allowed to strike the coast not only at the most critical point but at 8-mi intervals.(being a multiple of the SPLASH grid) on both sides of a location under study, and the storm surge profiles shifted along the coast accordingly. The calculations involved in this are explained in one of the reports cited (Myers 1975).

As the third step, all profiles in all shifted positions are randomly added to the astronomical tide. The time phasing of surge and astronomical tide is handled in a probabilistic manner as described in the report previously cited (Myers 1975). The range of astronomical tide oscillation is represented by four separate classes. The requisite analysis of a 19-yr cycle of the astronomical tide to obtain these ranges is further discussed in the next section. Since each surge profile has a prescribed frequency, as have the astronomical tides, all the profiles may be combined into a single tide frequency curve for a fixed coastal point.

As a fourth step, storm tides are similarly computed for the alongshore storms from the data listed in tables 1 to 5, and for the exiting and inland storms for locations north of Cape Hatteras (tables 1-3). To the south of Cape Hatteras, the occurrence of exiting storms is rather infrequent and storms bypassing inland are included in the landfalling category. For the fifth step, winter coastal storm-tide frequencies are also evaluated from tide gage records (sec.5). Finally, summing all the possibilities yields the total tide frequency.

Legend for Tables 1 to 5

θ_c = Orientation of coast, measured clockwise from north (deg).

P_o = Central pressure (mb).

D = Central pressure deficit (mb).

P_i = Proportion of total storms with indicated D value.

R = Distance from center of storm to principal belt of maximum winds (n.mi.)

P_r = Proportion of storms with indicated R value.

T = Forward speed of storm (kt).

P_t = Proportion of storms with indicated T value.

F = Frequency of storm tracks crossing coast (storm tracks per n.mi. of coast per year).

θ_L = Direction of entry or exit, measured clockwise from the coast (deg).

P_θ = Proportion of storms with indicated θ_L value.

L = Distance of storm track from coast inland or seaward (n.mi.).

F_a = Frequency of storm tracks crossing line normal to coast (storm tracks per n.mi. per year).

LL = Effective distance of storm over land (n.mi.).

Table 1.--Hurricane and tropical storm parameters
N.C.-Va. border. θ_c=346°

	P_o	D	P_i	R	P_r	T	P_t	F	θ_L	P_θ
SE Landfalling	934.8	78.4	.02	*	*	7.5	.2	.00033	140	1.0
	942.9	70.3	.03	*	*	11.3	.2			
	949.2	64.0	.05	23.8	.33	15.2	.2			
	955.8	57.4	.10	36.9	.33	20.0	.2			
	964.7	48.5	.20	42.8	.33	25.2	.1			
	975.2	38.0	.20			31.0	.1			
	985.0	28.2	.20							
	996.7	16.5	.20							
NE Landfalling	962.0	51.2	.02	23.8	.33	6.1	.2	.00021	93	1.0
	964.8	48.4	.03	36.9	.33	6.8	.2			
	968.8	44.4	.05	42.8	.33	7.5	.2			
	975.2	38.0	.10			8.7	.2			
	984.3	28.9	.20			10.4	.1			
	991.7	21.5	.20			12.9	.1			
	996.0	17.2	.20							
	999.6	13.6	.20							
Exiting	959.7	53.5	.1	23.8	.33	9.4	.3	.00240	233	.5
	967.9	45.3	.1	36.9	.33	15.2	.4		266	.5
	975.4	37.8	.2	42.8	.33	25.2	.3			
	985.1	28.1	.2							
	992.8	20.4	.2							
	1000.2	13.0	.2							

	L	F_a	LL	R	P_r	T	P_t	Remarks
Alongshore	5	.0008		*	*	12.5	.2	P_o, D, and P_i are the same as those for SE landfalling storms.
	15	.0008		23.8	.33	17.2	.2	
	25	.0009		36.9	.33	19.9	.2	
	35	.0011		42.8	.33	24.4	.2	
	50	.0012				29.9	.1	
	70	.0012				35.6	.1	
Inland	5	.0015	50	23.8	.33	11.2	.3	D's are adjusted from landfalling storms by eq (3) using LL and T values.
	15	.0016	60	36.9	.33	17.7	.4	
	25	.0017	65	42.8	.33	25.1	.3	
	35	.0017	70					
	50	.0013	90					

* SE landfalling and alongshore storms with P_o<945 mb:
R = 23.8 and 36.9 n.mi. are each assigned a probability of 0.5.

Table 2.--Hurricane and tropical storm parameters
Wright Monument, N.C. θ_c=337°

	P_o	D	P_i	R	P_r	T	P_t	F	θ_L	P_θ
SE Landfalling	933.9	79.3	.02	*	*	7.2	.2	.00037	145	1.0
	941.2	72.0	.03	*	*	10.8	.2			
	947.6	65.6	.05	23.3	.33	14.7	.2			
	955.2	58.0	.10	36.5	.33	19.3	.2			
	964.3	48.9	.20	42.7	.33	24.3	.1			
	974.9	38.3	.20			30.2	.1			
	985.3	27.9	.20							
	996.6	16.6	.20							
NE Landfalling	962.0	51.2	.02	23.3	.33	6.1	.2	.00037	98	1.0
	964.8	48.4	.03	36.5	.33	6.8	.2			
	968.8	44.4	.05	42.7	.33	7.5	.2			
	975.2	38.0	.10			8.7	.2			
	984.3	28.9	.20			10.4	.1			
	991.7	21.5	.20			12.9	.1			
	996.0	17.2	.20							
	999.6	13.6	.20							
Exiting	954.4	58.8	.1	23.3	.33	9.0	.3	.00273	238	.5
	963.9	49.3	.1	36.5	.33	14.7	.4		281	.5
	972.1	41.1	.2	42.7	.33	24.3	.3			
	982.7	30.5	.2							
	991.5	21.7	.2							
	999.1	14.1	.2							

	L	F_a	LL	R	P_r	T	P_t	Remarks
Alongshore	5	.0011		*	*	12.0	.2	P_o, D, and P_i are the same as those for SE landfalling storms.
	15	.0012		23.3	.33	16.3	.2	
	25	.0012		36.5	.33	19.2	.2	
	35	.0013		42.7	.33	23.3	.2	
	50	.0013				28.7	.1	
	70	.0014				34.4	.1	
Inland	5	.0014	20	23.3	.33	11.2	.3	D's are adjusted from landfalling storms by eq (3) using LL and T values.
	15	.0014	30	36.5	.33	17.7	.4	
	25	.0014	35	42.7	.33	25.1	.3	
	35	.0014	40					
	50	.0013	60					

* SE landfalling and alongshore storms with P_o<945 mb:

R = 23.3 and 36.5 n.mi. are each assigned a probability of 0.5.

Table 3.--Hurricane and tropical storm parameters

Salvo, N.C. θ_c=360°

	P_o	D	P_i	R	P_r	T	P_t	F	θ_L	P_θ
SE Landfalling	932.7	80.5	.02	*	*	6.8	.2	.00051	122	1.0
	939.7	73.5	.03	*	*	10.1	.2			
	946.4	66.8	.05	22.8	.33	13.8	.2			
	954.6	58.6	.10	36.0	.33	18.4	.2			
	964.1	49.1	.20	42.5	.33	23.2	.1			
	974.7	38.5	.20			29.3	.1			
	985.4	27.8	.20							
	996.6	16.6	.20							
NE Landfalling	962.0	51.2	.02	22.8	.33	6.1	.2	.00051	75	1.0
	964.8	48.4	.03	36.0	.33	6.8	.2			
	968.8	44.4	.05	42.5	.33	7.5	.2			
	975.2	38.0	.10			8.7	.2			
	984.3	28.9	.20			10.4	.1			
	991.7	21.5	.20			12.9	.1			
	996.0	17.2	.20							
	999.6	13.6	.20							
Exiting	947.2	66.0	.1	22.8	.33	8.4	.3	.00075	215	.5
	958.1	55.1	.1	36.0	.33	13.8	.4		248	.5
	967.6	45.6	.2	42.5	.33	23.2	.3			
	979.3	33.9	.2							
	989.3	23.9	.2							
	997.6	15.6	.2							

	L	F_a	LL	R	P_r	T	P_t	Remarks
Alongshore	5	.0018		*	*	11.4	.2	P_o, D, and P_i are the same as those for SE landfalling storms
	15	.0019		22.8	.33	15.5	.2	
	25	.0020		36.0	.33	18.2	.2	
	35	.0021		42.5	.33	22.3	.2	
	50	.0022				27.7	.1	
	70	.0022				33.2	.1	
Inland	<20	#		22.8	.33	11.2	.3	D's are adjusted from landfalling storms by eq (3) using LL and T values.
	25	.0012	5	36.0	.33	17.7	.4	
	35	.0012	10	42.5	.33	25.1	.3	
	50	.0012	20					

* SE landfalling and alongshore storms with P_o<945 mb: R = 22.8 and 36.0 n.mi. are each assigned a probability of 0.5.

included with landfalling storms

Table 4.--Hurricane and tropical storm parameters
Ocracoke, N.C. θ_c=55°

	P_o	D	P_i	R	P_r	T	P_t	F	θ_L	P_θ
Landfalling	930.0	83.2	.02	*	*	6.5	.2	.00159	93	.33
	936.7	76.5	.03	*	*	9.4	.2		124	.33
	944.2	69.0	.05	21.0	.33	12.7	.2		147	.33
	953.2	60.0	.10	34.5	.33	16.8	.2			
	963.8	49.4	.20	42.0	.33	21.5	.1			
	976.2	37.0	.20			27.3	.1			
	987.6	25.6	.20							
	996.3	16.9	.20							

	L	F_a	LL	R	P_r	T	P_t	Remarks
Alongshore	5	.0030		*	*	11.1	.2	P_o, D, and P_i are the same as those for landfalling storms.
	15	.0045		21.0	.33	14.7	.2	
	25	.0056		34.5	.33	17.3	.2	
	35	.0059		42.0	.33	21.3	.2	
	50	.0055				26.5	.1	
	70	.0051				31.8	.1	

* Landfalling and alongshore storms with P_o<940 mb:
R = 21.0 and 34.5 n.mi. are each assigned a probability of 0.5.

Table 5.--Hurricane and tropical storm parameters
Cape Lookout, N.C. θ_c=90°

	P_o	D	P_i	R	P_r	T	P_t	F	θ_L	P_θ
Landfalling	928.5	84.7	.02	*	*	5.3	.1	.00155	044	.33
	935.6	77.6	.03	*	*	8.0	.2		086	.33
	943.3	69.9	.05	20.4	.33	10.7	.2		112	.33
	952.9	60.3	.10	33.6	.33	14.8	.2			
	963.5	49.7	.20	41.9	.33	19.1	.2			
	976.1	37.1	.20			25.8	.1			
	987.5	25.7	.20							
	996.2	17.0	.20							

	L	F_a	LL	R	P_r	T	P_t	Remarks
Alongshore	4	.0038		*	*	9.0	.1	P_o, D, and P_i are the same as those for landfalling storms.
	13	.0059		20.4	.33	12.3	.2	
	22	.0065		33.6	.33	15.0	.2	
	30	.0066		41.9	.33	17.9	.2	
	43	.0062				23.1	.2	
	61	.0058				29.4	.1	

* Landfalling and alongshore storms with P_o<940 mb:
R = 20.4 and 33.6 n.mi. are each assigned a probability of 0.5.

6.2 Astronomical Tides

Most of the combinations of forces producing the astronomical tides are experienced during a 19-yr cycle. There is also a seasonal variation in the mean water level with a maximum in September-October. The months July, August, September, and the first half of October are taken to represent the hurricane season. Astronomical high and low tides at Morehead City and Avon, N.C., and Virginia Beach, Va., for these representative months were recomputed for a 19-yr period by running the standard tide computation program written by Pore and Cummings (1967). The accumulated frequencies of the high and low tides were calculated separately by months, then weighted in proportion to hurricane occurrences in each month (July 13%, August 27%, September 39%, October 21%). The weighted mean distributions are shown for Avon, N.C. in figure 12. The resulting probability distributions for Morehead City are almost the same as those for Avon. The range of high and low tides at Virginia Beach, Va., is slightly greater than that of Avon, N.C. Interpolating from the probability curves of the latter two stations leads to distributions used in tide frequency analyses for locations along the northern portion of the study area, while the probability distributions for Avon are adopted for locations to the south. As in previous studies, each distribution is divided into four class interval values of equal range. The representative astronomical tide marigrams needed to combine with each hurricane surge marigram were then approximated as cosine waves with a period of 12.42 hrs oscillating between corresponding high tide and low tide class interval values. This assumes that the highest high tides occur with the lowest low tides, etc.

6.3 Tide Frequencies at Selected Points

The tide frequency curves for the five classes of storms, landfalling, alongshore, inland, and exiting hurricanes and tropical storms, and winter coastal storms, are plotted together on figure 13 and combined to give an all-storm frequency curve for Wright Monument. Figure 14 is a similar plot for Ocracoke Inlet, N.C., for the classes of storms applicable there. The all-storms frequency curves for Cape Lookout, Salvo, N.C., and at the N.C.-Va. border are shown in figure 15. The tide levels are stated as heights above local mean sea level, adjusted to the 1941-59 epoch. Datum levels and differences between datums in use are covered in par. 6.5. The "open coast" tide frequencies apply to ocean beaches at or near the locations indicated. It should be emphasized that these frequency values are of still-water levels on the open coast that would be measured in a tide gage house or other enclosure, excluding wave action. The destructive effects of waves on the beach front must be taken into account separately. In insurance rating this is taken into account by the ocean front "velocity zone."

Local effects can modify the elevation of the storm tide. Local features diminishing "open coast" elevations in the landward direction include narrow passes and inlets and obstructions to inundation such as dunes and swamp vegetation. Converging shores of bays and strong winds over long fetches of shallow water (wind "setup") have the opposite effect. The net results of these effects can result in either higher or lower storm tide levels of a given mean return period at estuarine, bay, and inland locations compared to the open coast. These differences have to be determined by localized studies.

The hurricane surge data presented here are only a portion of that needed for such localized studies.

6.4 Adjustment Along the Coast

The estimated tide frequencies for locations other than those selected for computation along this stretch of the coast were obtained by interpolation. The interpolation was based on consideration of the frequency of storms, the variation in the shoaling factor (fig. 10), and the trend in the hurricane climatology parameters along the coast. Figure 16 shows the variation of the total tide heights along the coast for 10-, 50-, 100-, and 500-yr return periods, scaled from these diagrams and interpolated as indicated.

6.5 Reference Datum

The National Ocean Survey, NOAA, and its component, the National Geodetic Survey, have developed the following standards for elevation control. Both standards are defined here for convenience in consistent application of the results of this study. The difference between the two is not large.

The National Geodetic Vertical Datum (NGVD) of 1929. This is a level surface, perpendicular everywhere to the earth's gravity field. Its position is defined by precise leveling between geodetic benchmarks throughout the United States. Elevation contours on current topographic maps are generally related to this datum. The NGVD is approximately, but not exactly, at the mean level of the sea on the coasts. It cannot coincide exactly because of the fact that the sea is not a geopotential surface, and sea level has risen since 1929.

Local Mean Sea Level (local MSL). The arithmetic mean hourly sea-level heights over a specific 19-yr series of observations. A nineteen-year period is required to complete certain lunar cycles (Shureman 1975). The reference 19-yr period, or tidal epoch, is changed about every 25 years. Storm tide levels in this report are referred to local MSL, 1941-59 epoch. Two reasons for using local MSL in coastal work are: First, this datum is defined in terms of actual sea conditions, and therefore meets legal requirements for establishing "mean low water" and the like which are determined from tide observations. Second, it is much more economical in many coastal communities to establish a benchmark by observation of the height of the sea over a period of time by a gage installed for the purpose, than by leveling from the geodetic net. The National Ocean Survey has an active program of establishing tidal benchmarks in this way. Short-period or recent records from these gages are adjusted to the 1941-59 epoch based on comparison with simultaneous tide observations at long-record primary stations.

Differences between NVGD and local MSL have been established at primary tide gages by leveling, and at certain subordinate tide stations. These differences are interpolated between points at which they have been established. Differences determined in this way in the study area are within ± 0.1 ft.

The methods of developing storm-tide frequencies in this study inherently yield heights above local MSL. The heights of the frequency graphs are in terms of this datum referred to the 1941-59 epoch. Adjustment to NVGD is essentially zero for the stretch of coast under study, as indicated.

Additional information on tidal and geodetic datums can be obtained from the National Ocean Survey, Rockville, Md., 20852. The tidal datum program is described in the NOAA publication "Variability of Tidal Datum and Accuracy in Determining Datums from Short Series of Observations" (Swanson 1974).

Local MSL relative to land is increasing slowly on the east coast, at the rate of about a foot a century. Data on trends in sea level relative to land are given in the above cited publication and by Hicks and Crosby (1974). This trend is thought to be due mostly to slow subsidence of the land, but may also reflect change in volume of water in the sea from melting of ice. No adjustment has been made for this secular trend in this study.

6.6 Comparison of Frequency Curve

Figure 17 shows a tide frequency curve (dashed line) for Ocracoke, N.C., and tide levels of 10 selected hurricanes of recent years (plotted data points) at Ocracoke Village on the shores of Pamlico Sound, close to Ocracoke Inlet, reproduced from a report prepared by the Corps of Engineers, Wilmington, N.C., District (1963). The tide frequency curve for Ocracoke Inlet of the present study (copied from fig. 14 curve d) is also shown in the same diagram (solid line). The tide levels at the 100-yr and 500-yr return period on both curves reveal a difference of about 0.2 ft. This comparison is intended to verify the correspondence of the computed frequency curve in figure 14 to the local historical record.

7. RELATION OF THIS REPORT TO DISASTER PLANNING

The most recent disastrous display of hurricane forces on the U. S. coast was by Camille, which struck the Bay St. Louis - Pass Christian - Gulfport - Biloxi, Miss., areas in 1969. According to high-water marks, the storm tide reached a level of 24.6 ft above mean sea level (Corps of Engineers 1969). The central pressure at landfall was about 908 mb (Ho et al. 1975). This is the most intense hurricane so far to strike the United States mainland during the period of record keeping. Other disasters could also be recounted, including Hazel at the N.C.-S.C. border in 1954 and the Ga.-S.C. hurricane of 1893. All of the eastern seaboard south of Cape Hatteras is exposed to these. For this part of the area of this study, the National Weather Service recommends a repeat of Camille, the worst hurricane to strike the mainland, as a disaster planning objective without regard to the statistical frequency of such a storm at an individual point. Such a storm on a critical path for the south end of the study area of this report would reproduce a maximum of about 13 to 15 ft MSL.

North of Cape Hatteras a hurricane slightly less intense than Camille (because of mid-latitude modifications) making a direct strike from the southeast is a very real, if rare, possibility. Disaster and evacuation planning should take into account the possibility of storm tide somewhat above the 500-yr level of figure 16.

The central purpose of this report is to develop actuarial frequencies for insurance rating and related uses; therefore, all frequencies, including the coastal profiles of figure 16, are stated in terms of probabilities or mean recurrence intervals at points. The likelihood of Camille or any other given intensity of storm somewhere within the study area in any given year is much greater than the point recurrence interval for the same storm, a difference that needs to be taken into account in regional planning against disasters. Regional disaster planning should be based on studies for that particular purpose.

8. COORDINATION AND COMPARISON WITH OTHER REPORTS

This report has been coordinated with the Corps of Engineers, Department of the Army, which has made and is making various Flood Insurance studies in the area.

Comparison with frequency levels in earlier studies for Outer Banks communities on the ocean side of the island, made during the first part of the Flood Insurance Program, are given in table 6.

The tide frequencies on the open coast at Cape Lookout, N.C., are the same as in a report for North Carolina, south of Cape Lookout, prepared by NOAA for the Federal Insurance Administration (Ho and Tracey 1975).

Table 6.--Comparison of tide frequencies

Location and agency studies	Tide level for return period		
	10-yr	100-yr (ft MSL)	500-yr
Nags Head, N.C.			
FIS study*, September 1972	6.4	8.8	10.0
Present study	5.6	9.0	11.5
Kill Devil Hills, N.C.			
FIS study*, October 1972	6.4	8.8	10.0
Present study	5.6	9.0	11.6

*Flood Insurance Study prepared for FIA by Corps of Engineers, U. S. Army, Wilmington, N.C., District.

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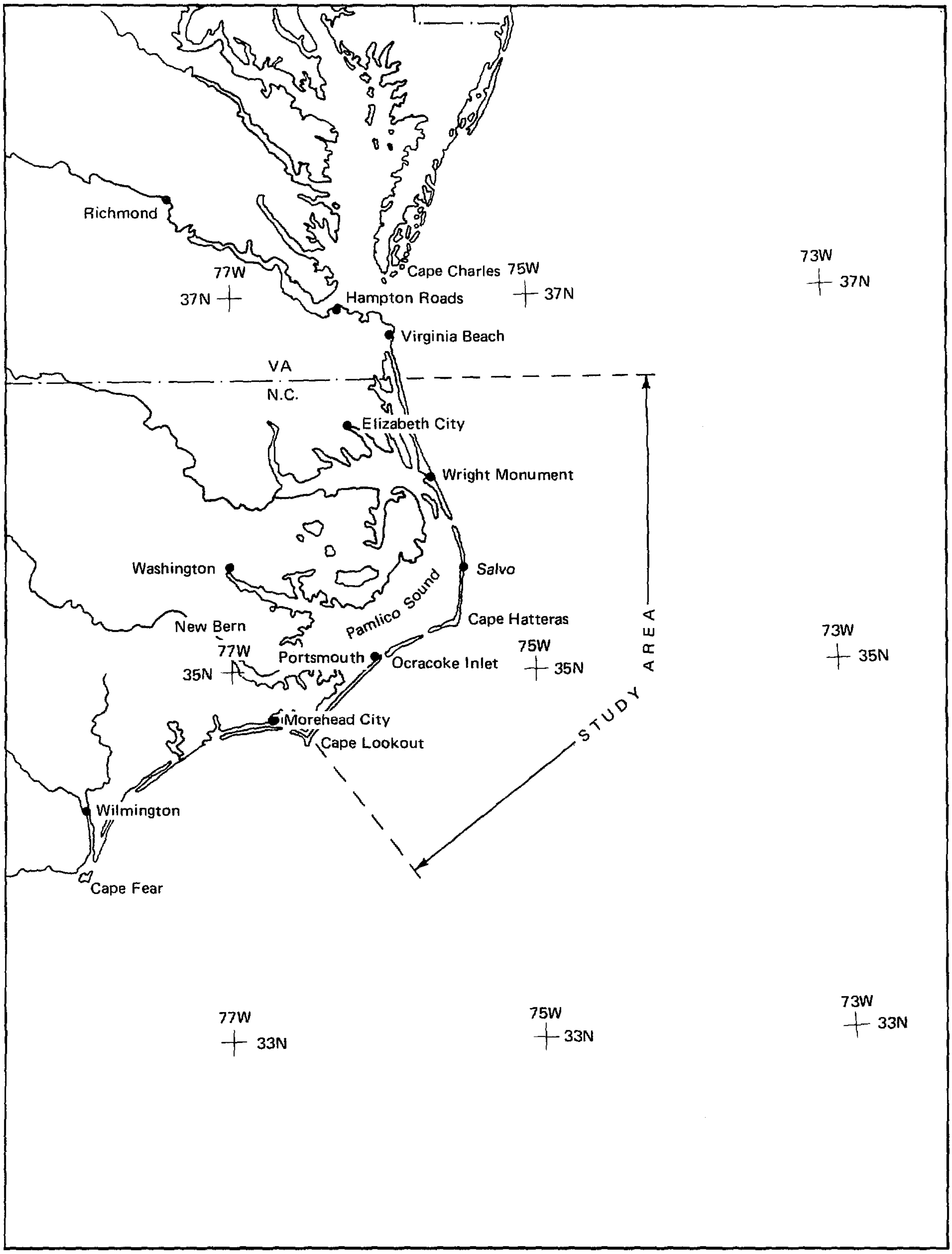

Figure 1.—Location map.

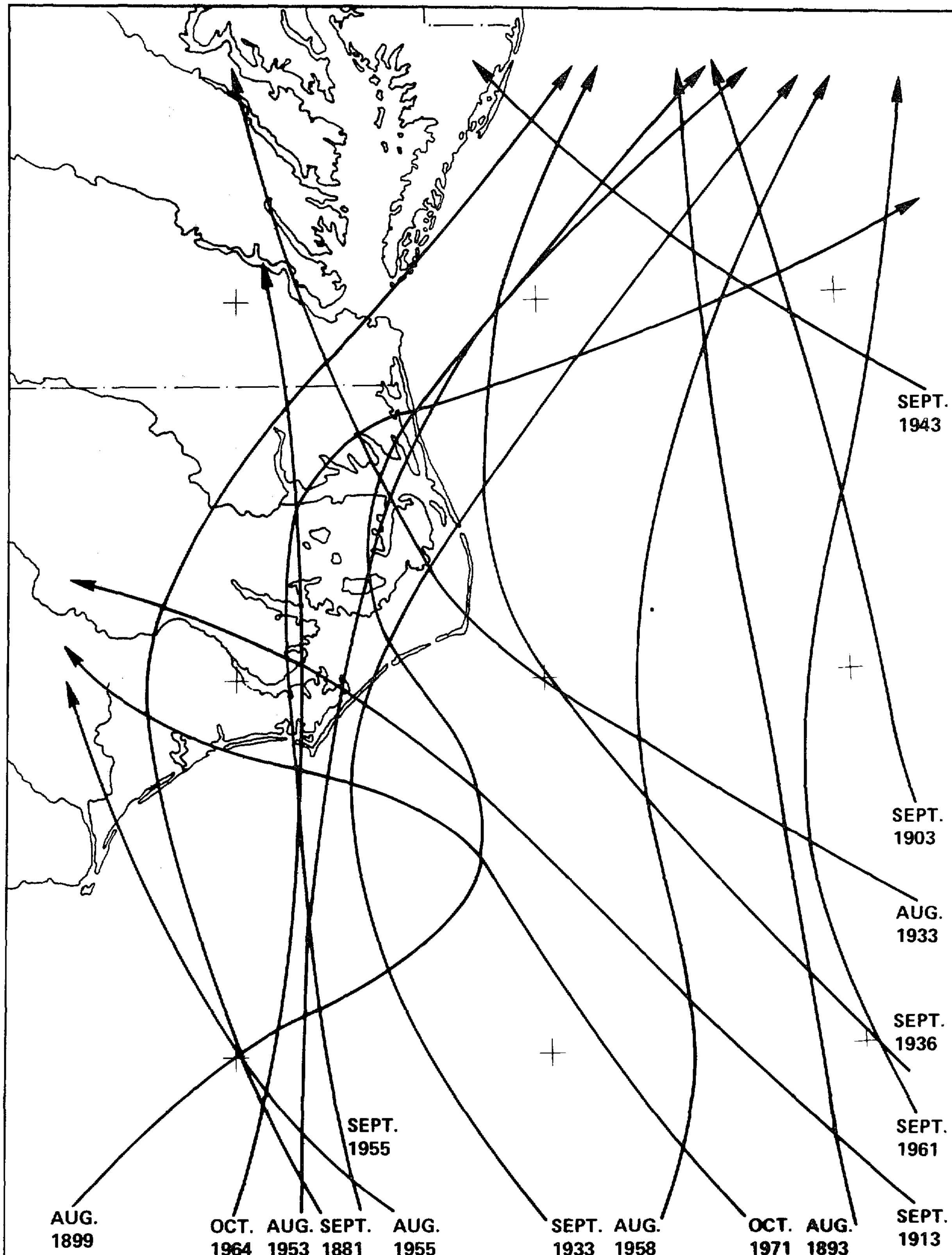

Figure 2.--Tracks of major hurricanes from the southeast quadrant affecting the study area, 1871-1974.

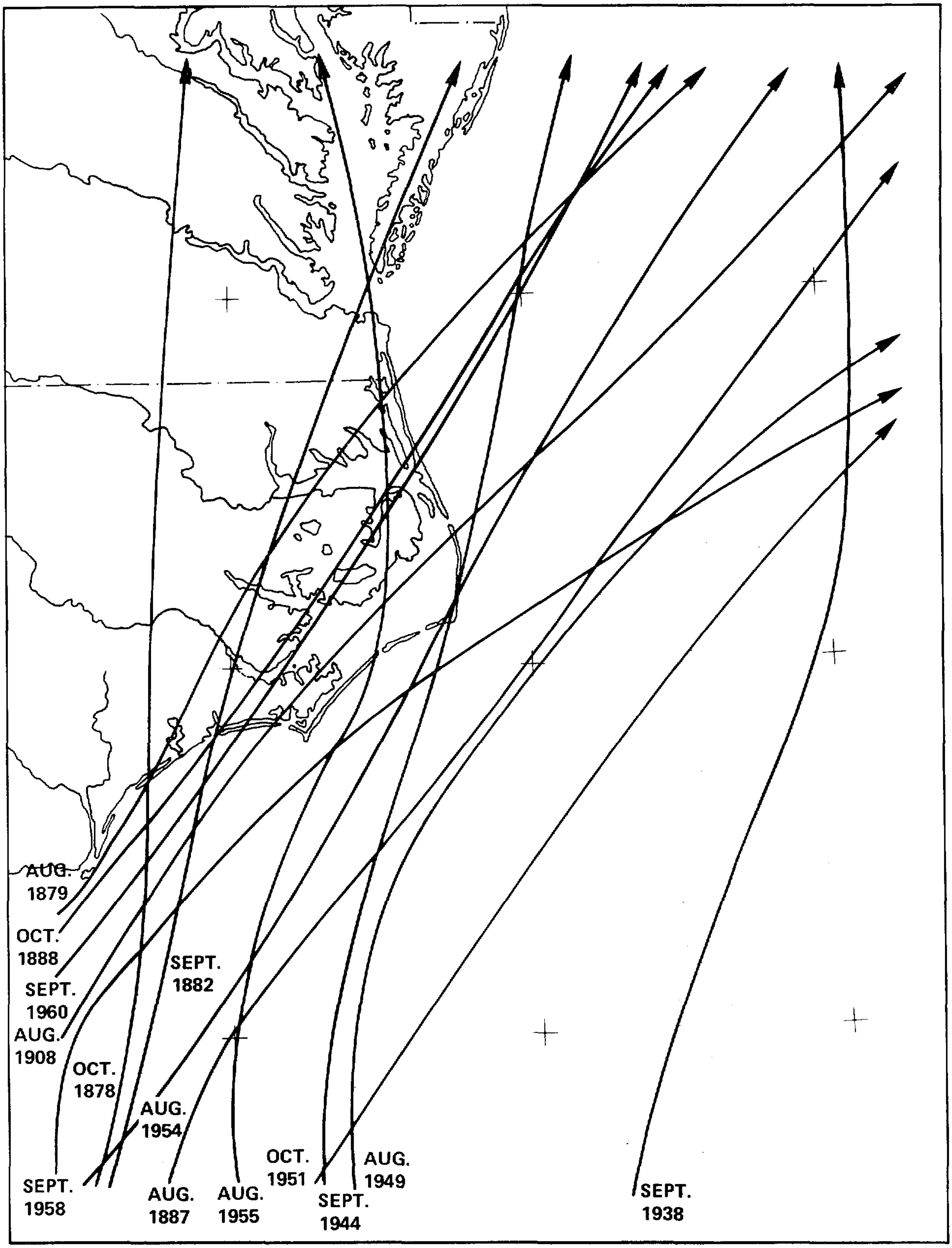

Figure 3.--Same as figure 2 but for hurricanes from the southwest quadrant.

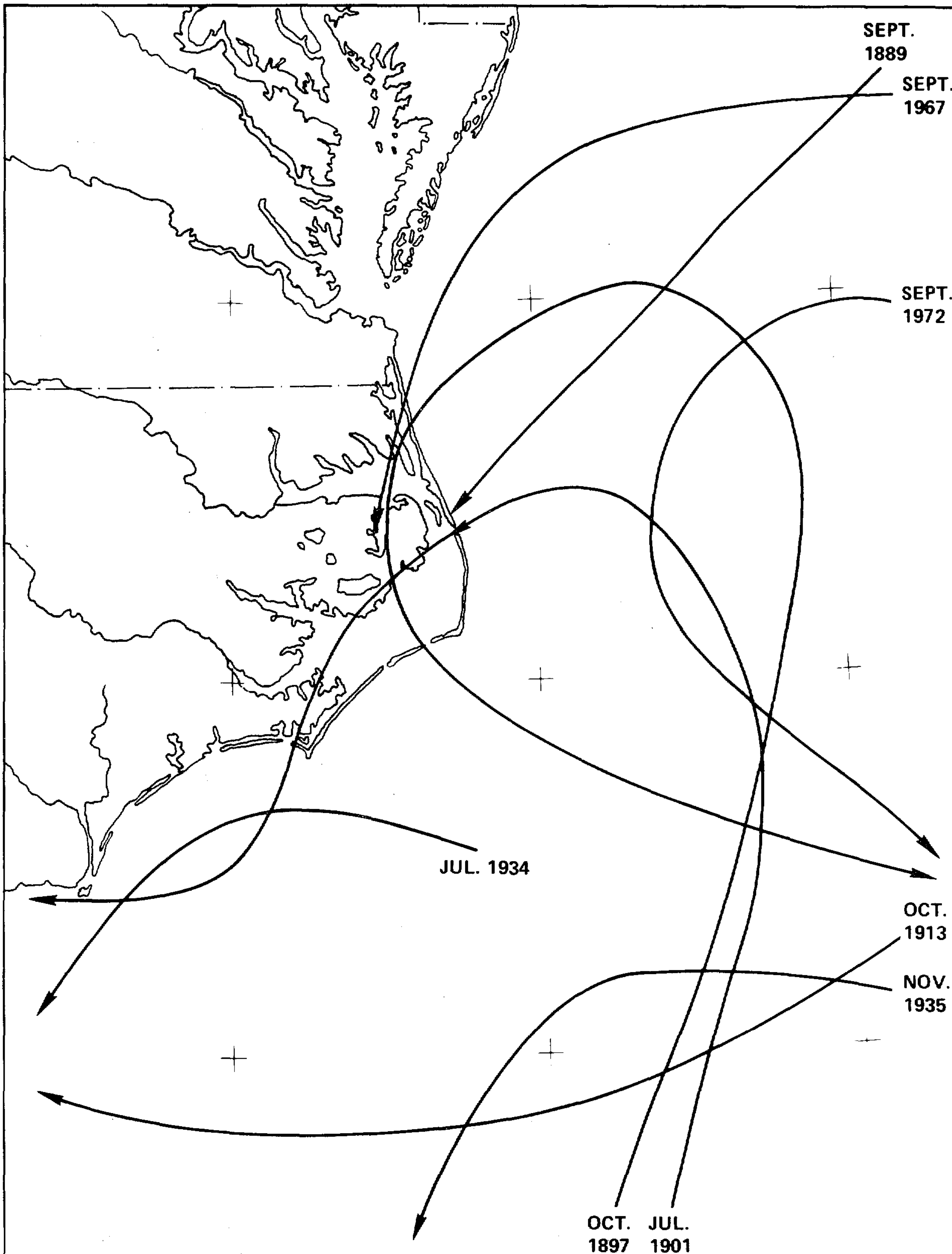

Figure 4.—Track of tropical storms and hurricanes showing motion from northeast.

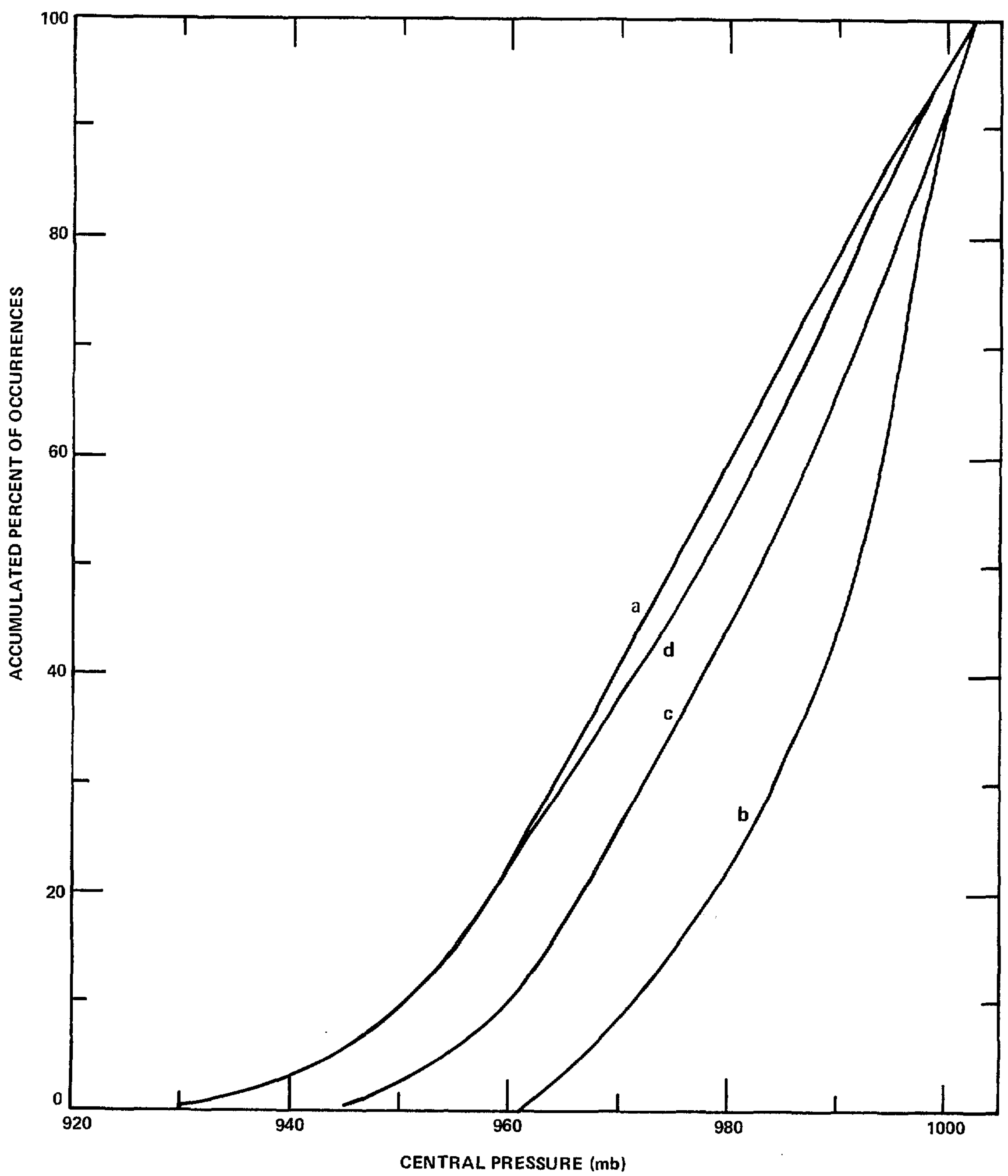

Figure 5.--Probability distribution of central pressure of hurricanes and tropical storms adopted for Wright Monument, N.C., (a) landfalling storms from the southeast quadrant and alongshore storms, (b) landfalling storms from the northeast quadrant, (c) exiting storms, and (d) all landfalling storms, reproduced from Climatology Report.

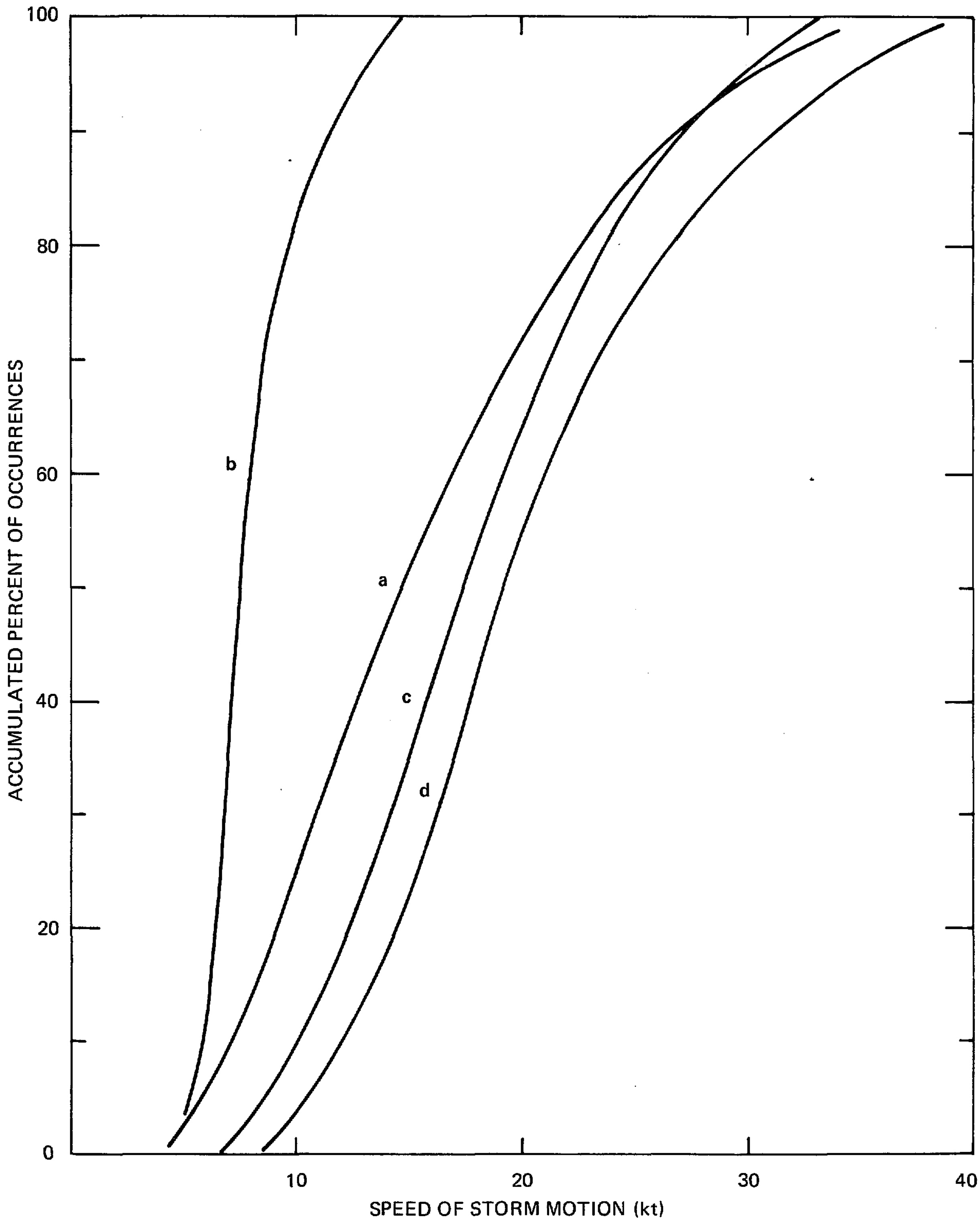

Figure 6.--Probability distributions of speed of storm motion adapted for Wright Monument, N.C., for (a) landfalling storms from the southeast quadrant and exiting storms, (b) landfalling storms from the northeast quadrant, (c) inland storms, and (d) alongshore storms.

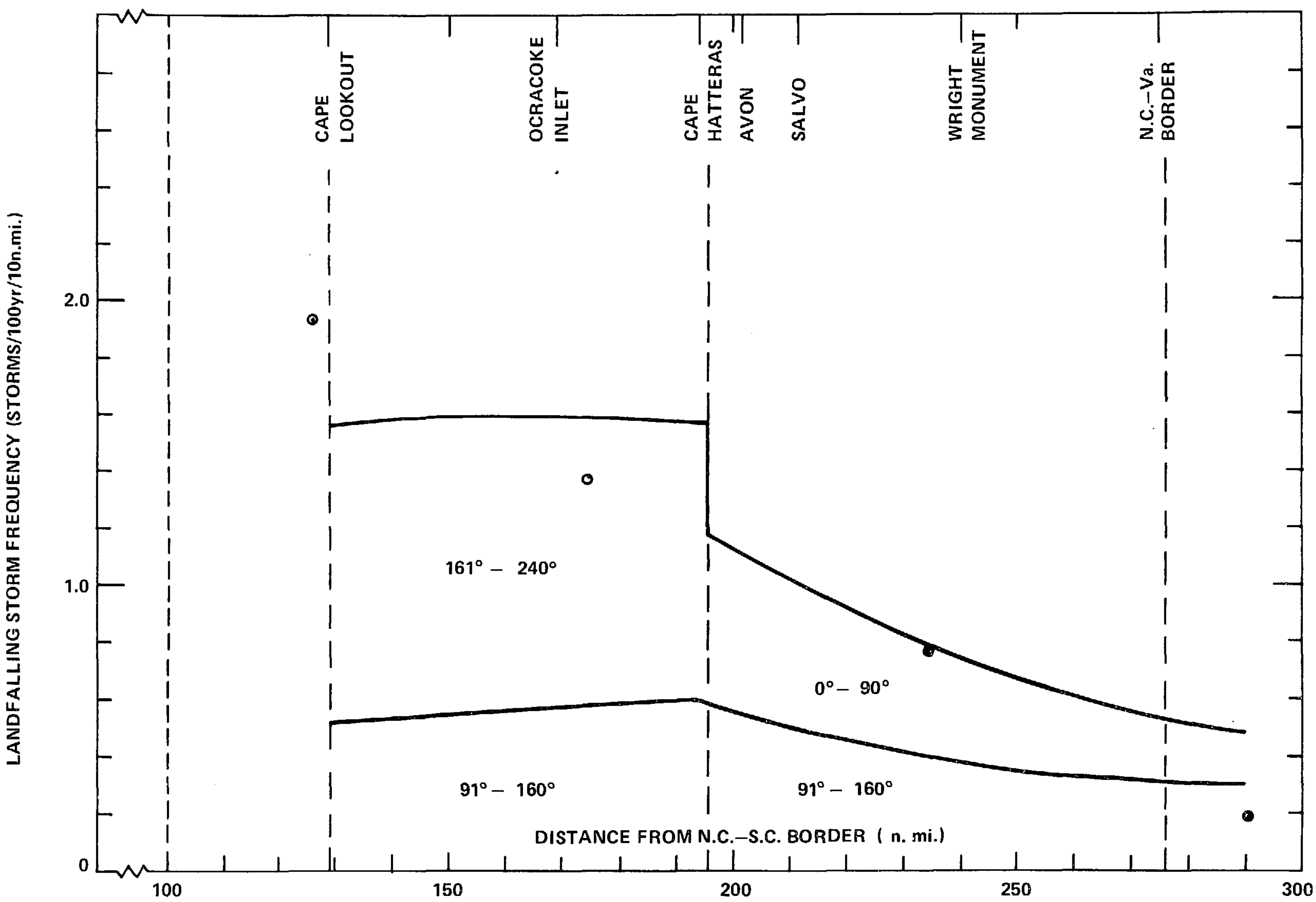

Figure 7.--Frequency of landfalling hurricanes and tropical storms. Circled dots are count for 50-n.mi. segments from Climatology Report.

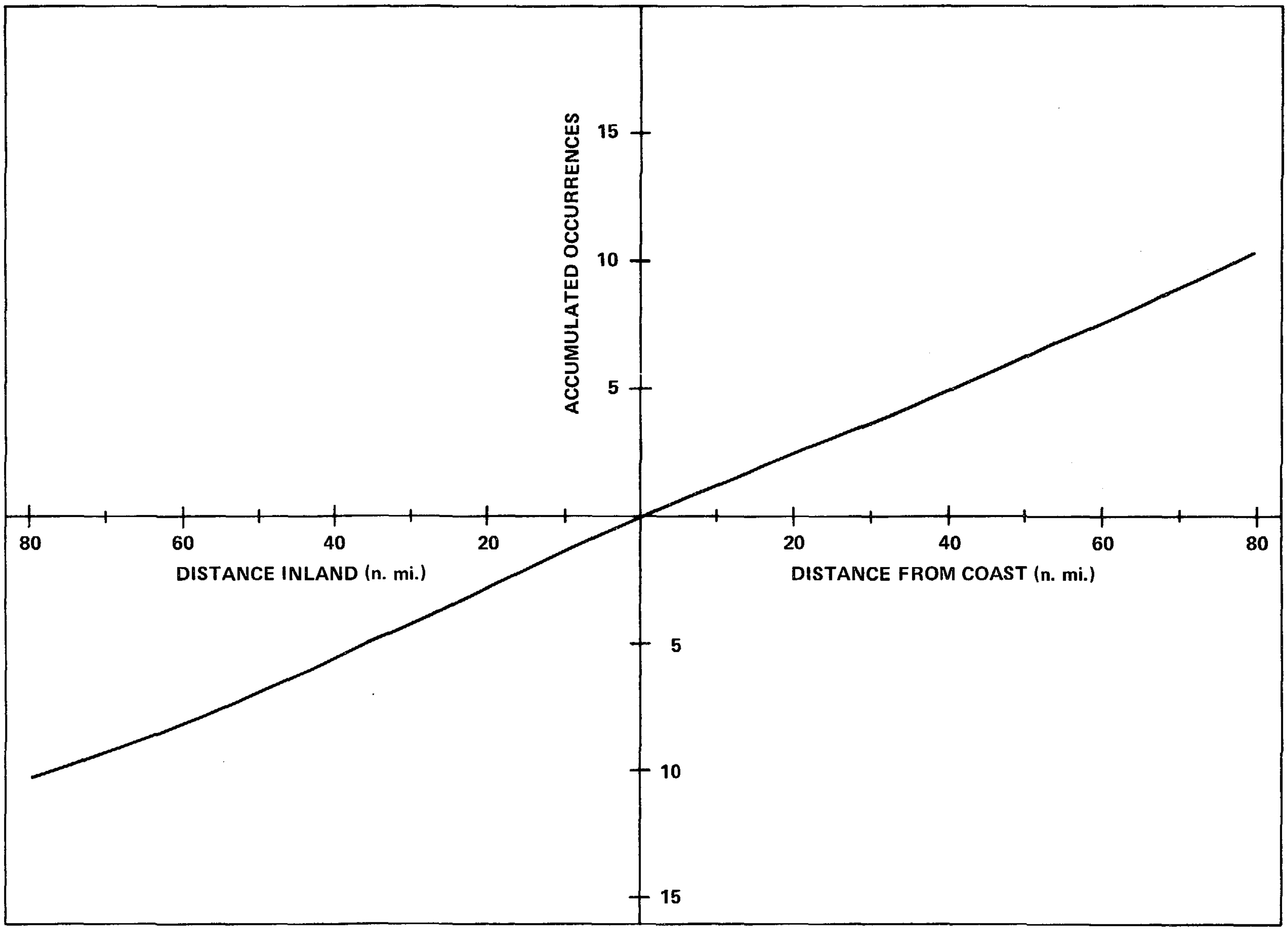

Figure 8.—Accumulative frequency of alongshore and inland hurricanes and tropical storms for Wright Monument, N.C., 1871-1974.

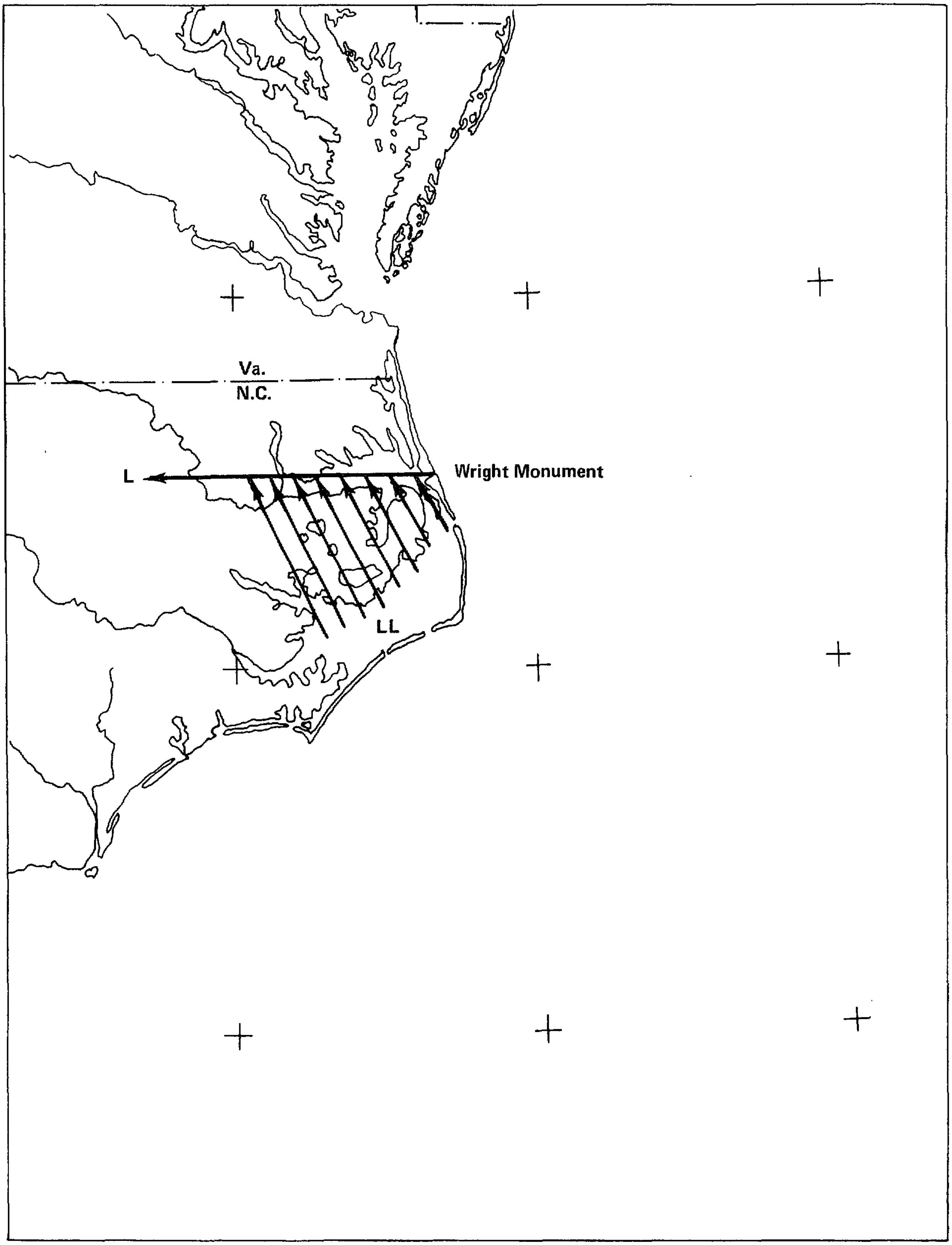

Figure 9.--Schematic diagram illustrating distances L and LL for hurricanes inland.

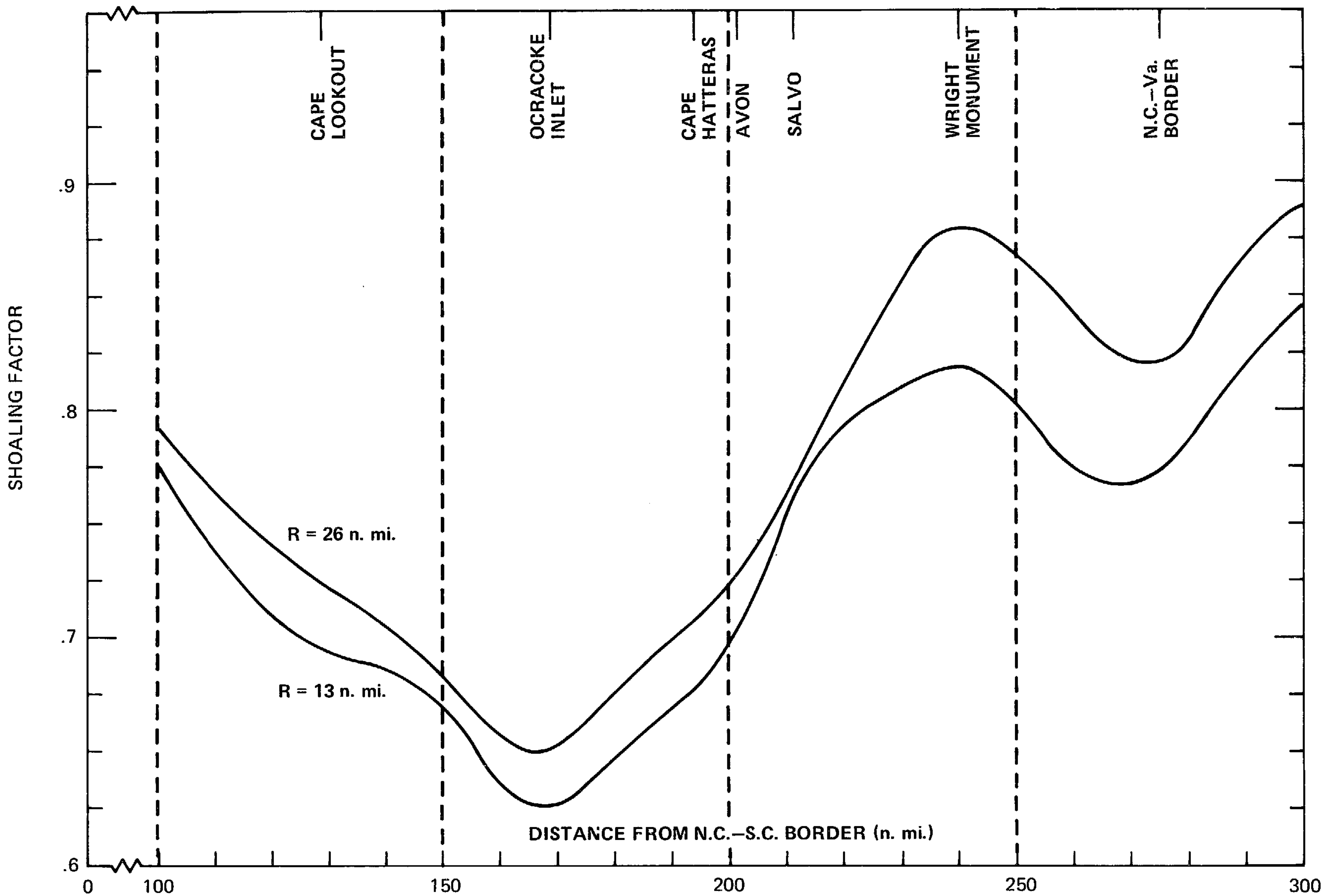

Figure 10.—Shoaling factor, North Carolina coast north of Cape Lookout. Adapted from Barrientos and Chen (1975).

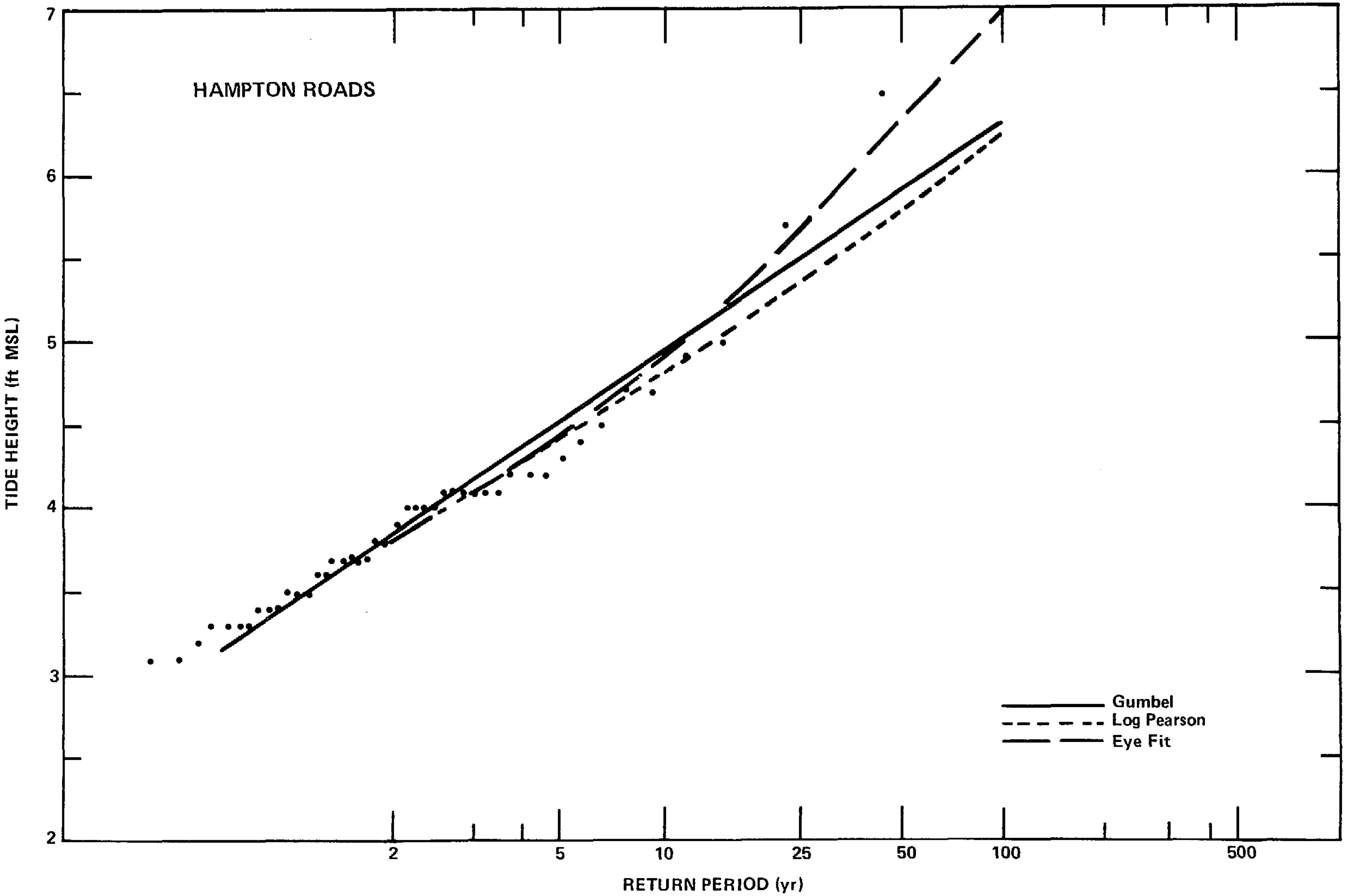

Figure 11.—Tide frequencies at Hampton Roads, Va., from winter coastal storms. Plotted points are seasonal (October–May) maxima.

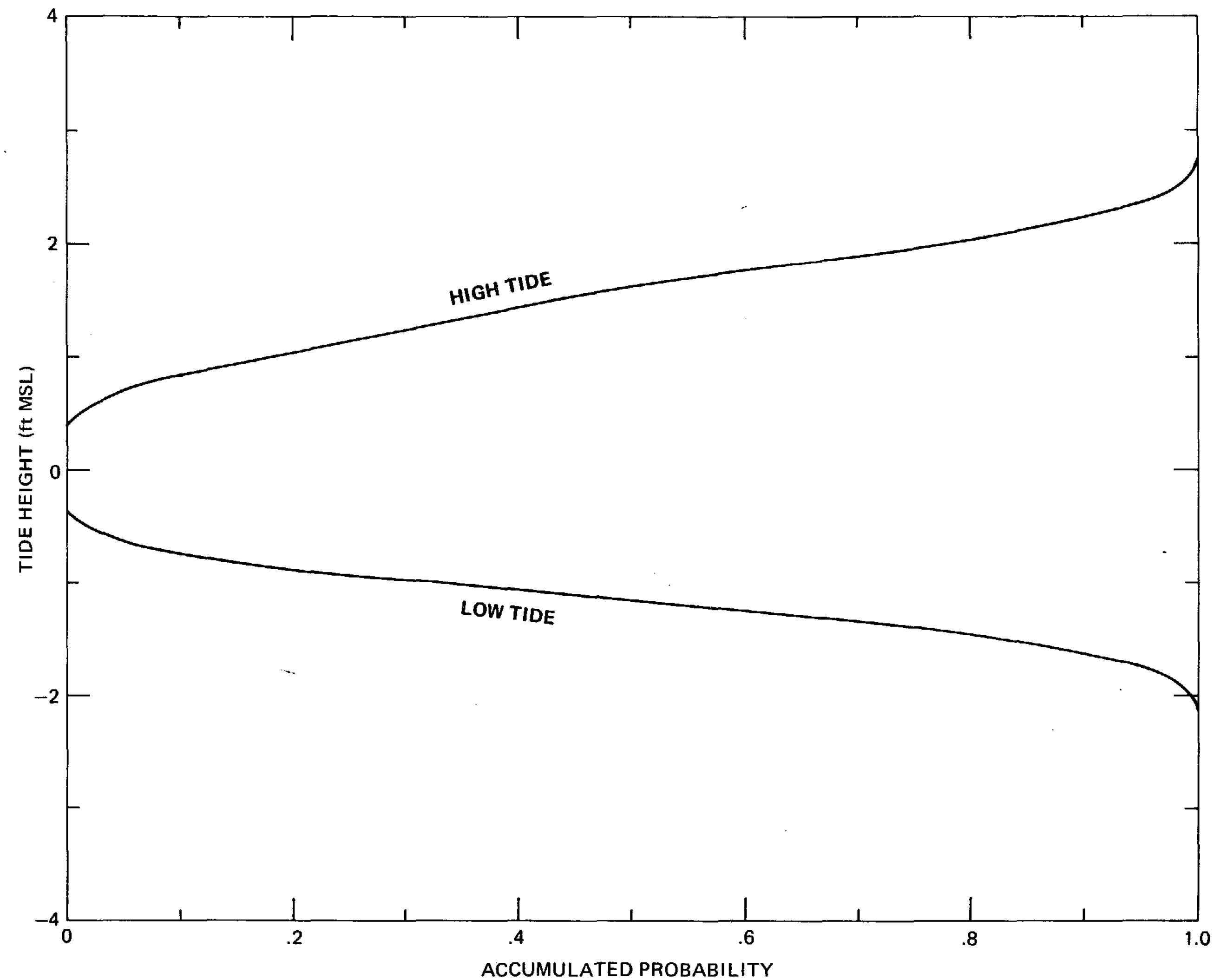

Figure 12.—Probability distribution of astronomical high and low tides for hurricane season, Avon, N.C., 1955–1973.

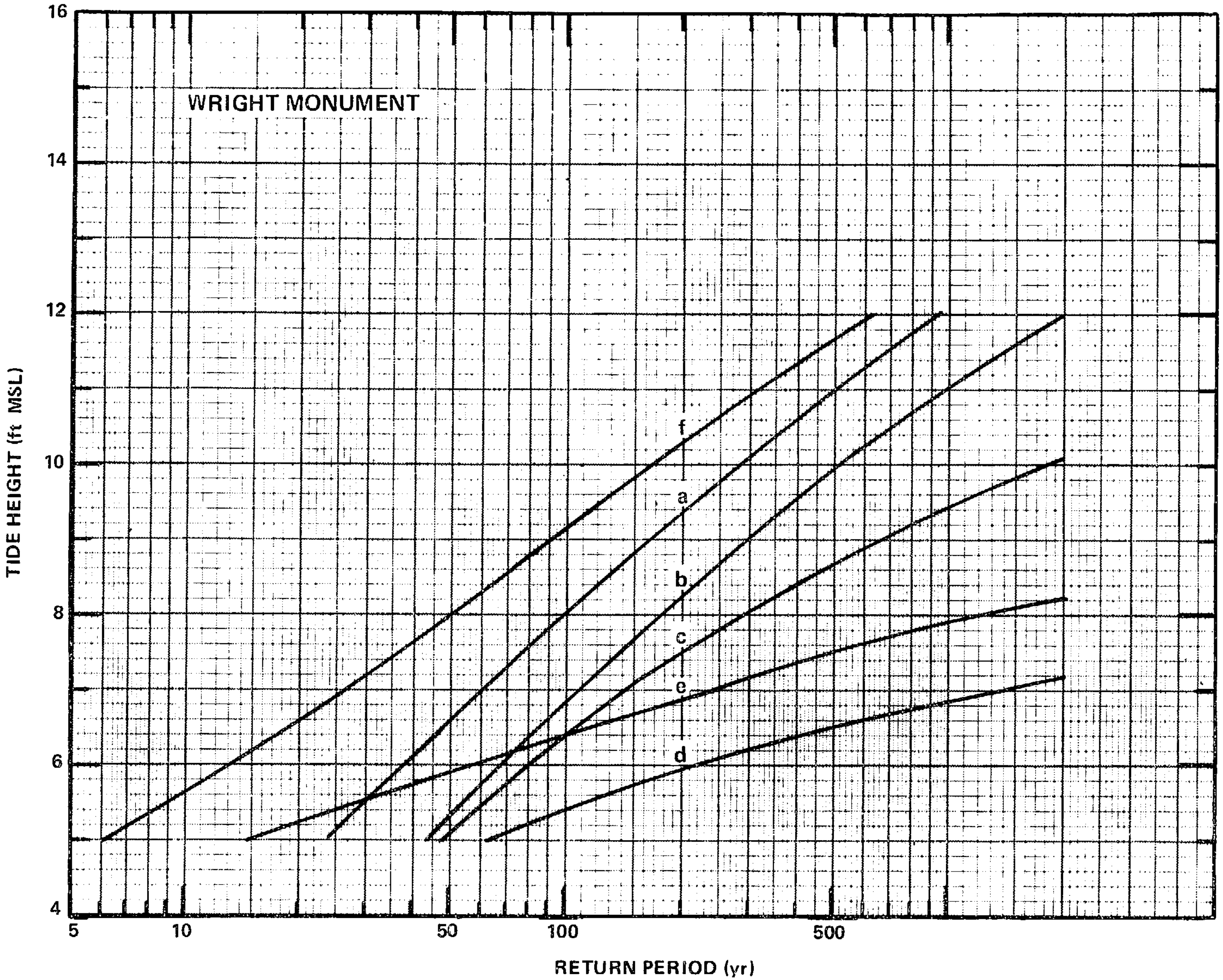

Figure 13.-- Tide frequencies at Wright Monument, N.C., for several classes of storms: (a) landfalling, (b) alongshore, (c) inland, and (d) exiting hurricanes and tropical storms; (e) winter storms; (f) all storms.

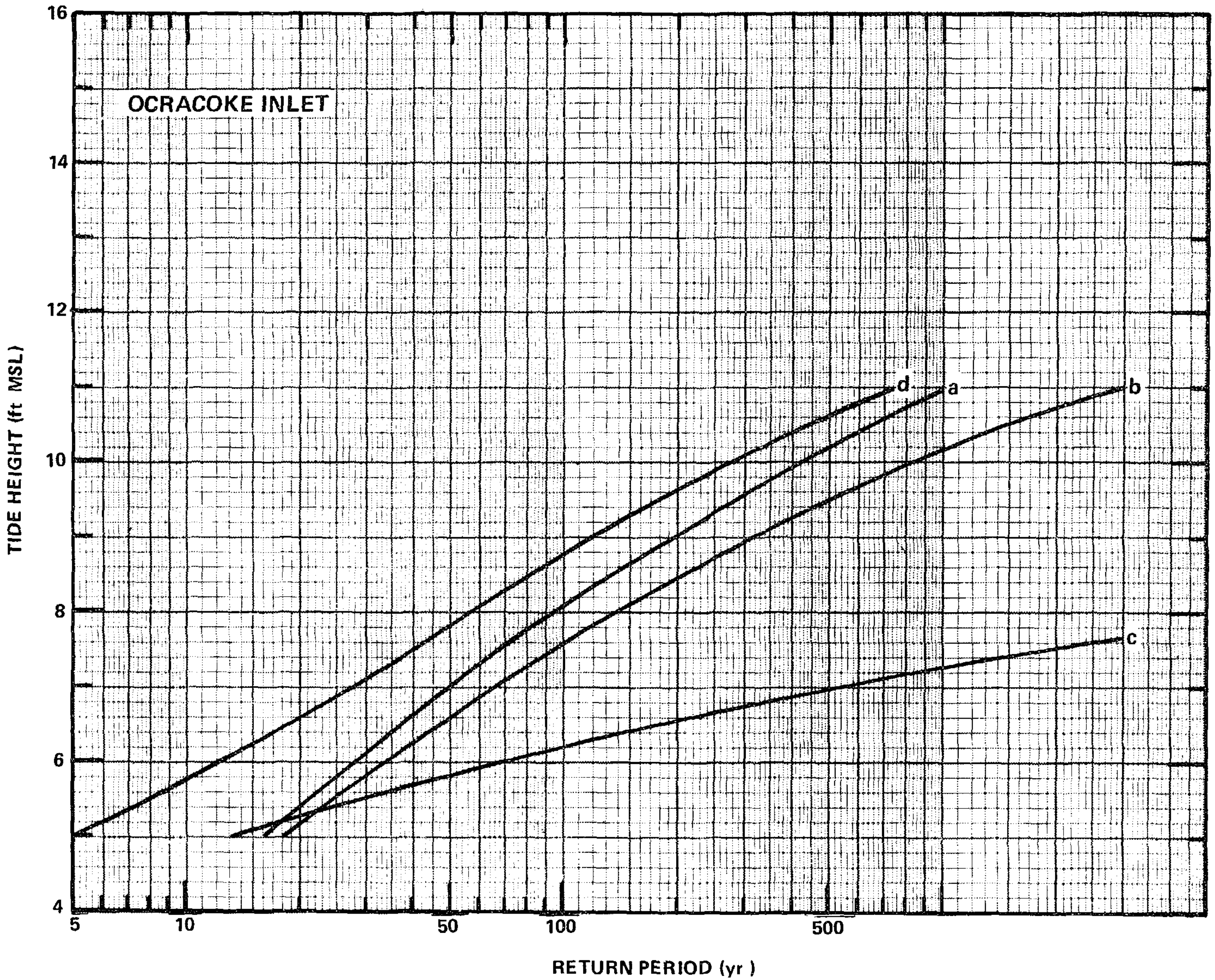

Figure 14.—Tide frequencies at Ocracoke Inlet for several classes of storms: (a) landfalling, and (b) alongshore hurricanes and tropical storms; (c) winter storms; (d) all storms.

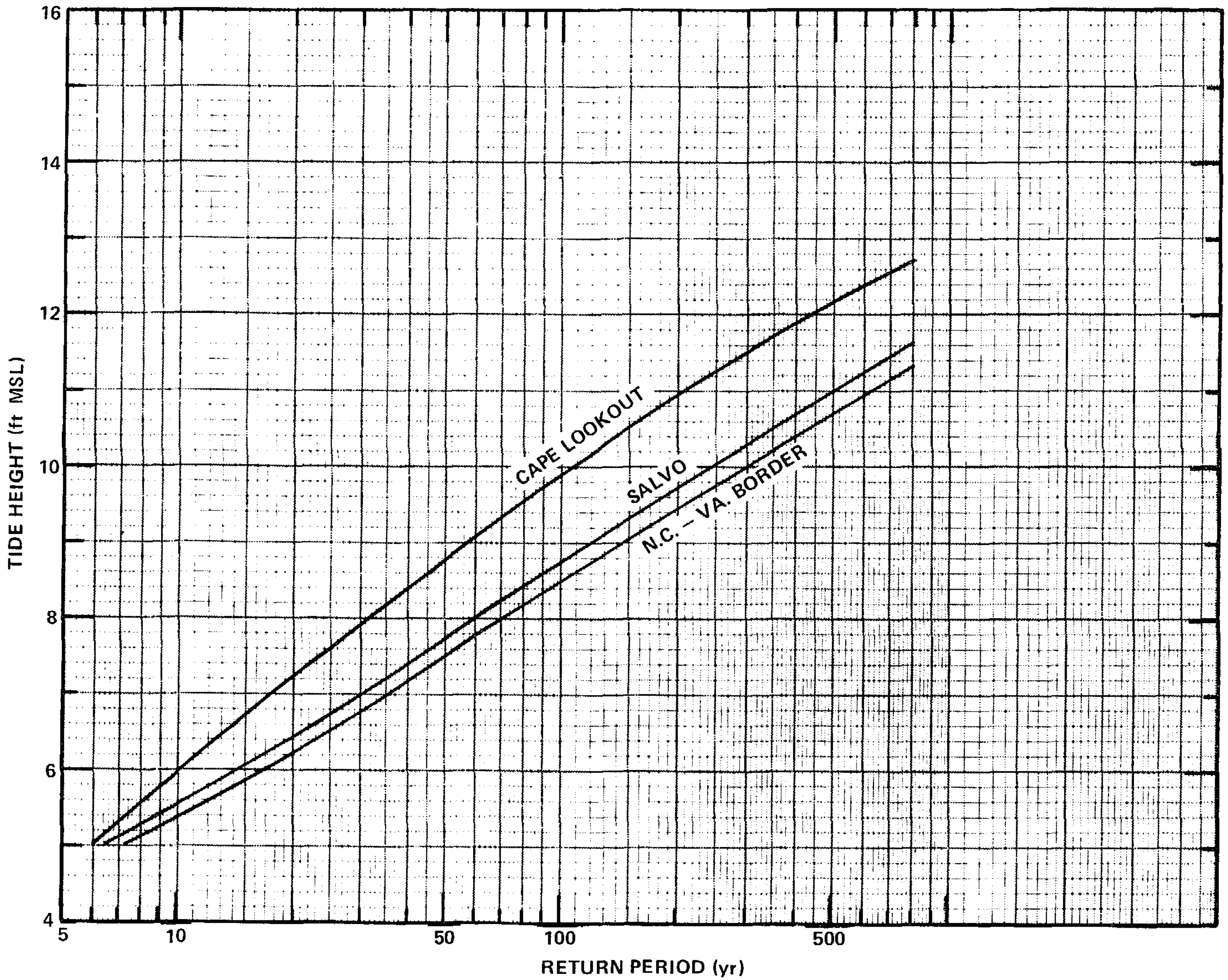

Figure 15.—Total tide frequencies at selected points on the open coast at Cape Lookout, and Salvo, N.C., and at the N.C.–Va. border.

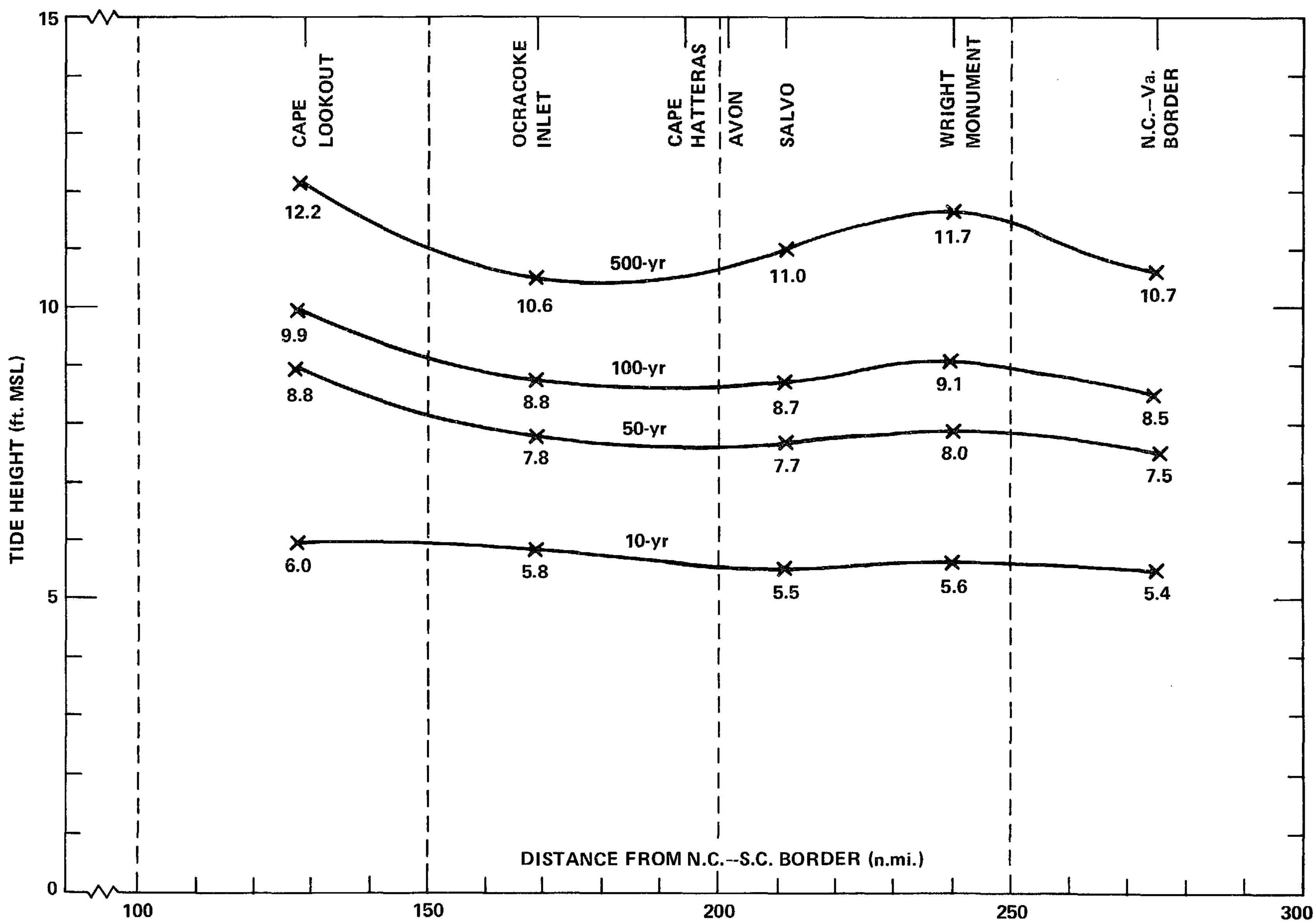

Figure 16.--Coastal tide frequencies. North Carolina, north of Cape Lookout.

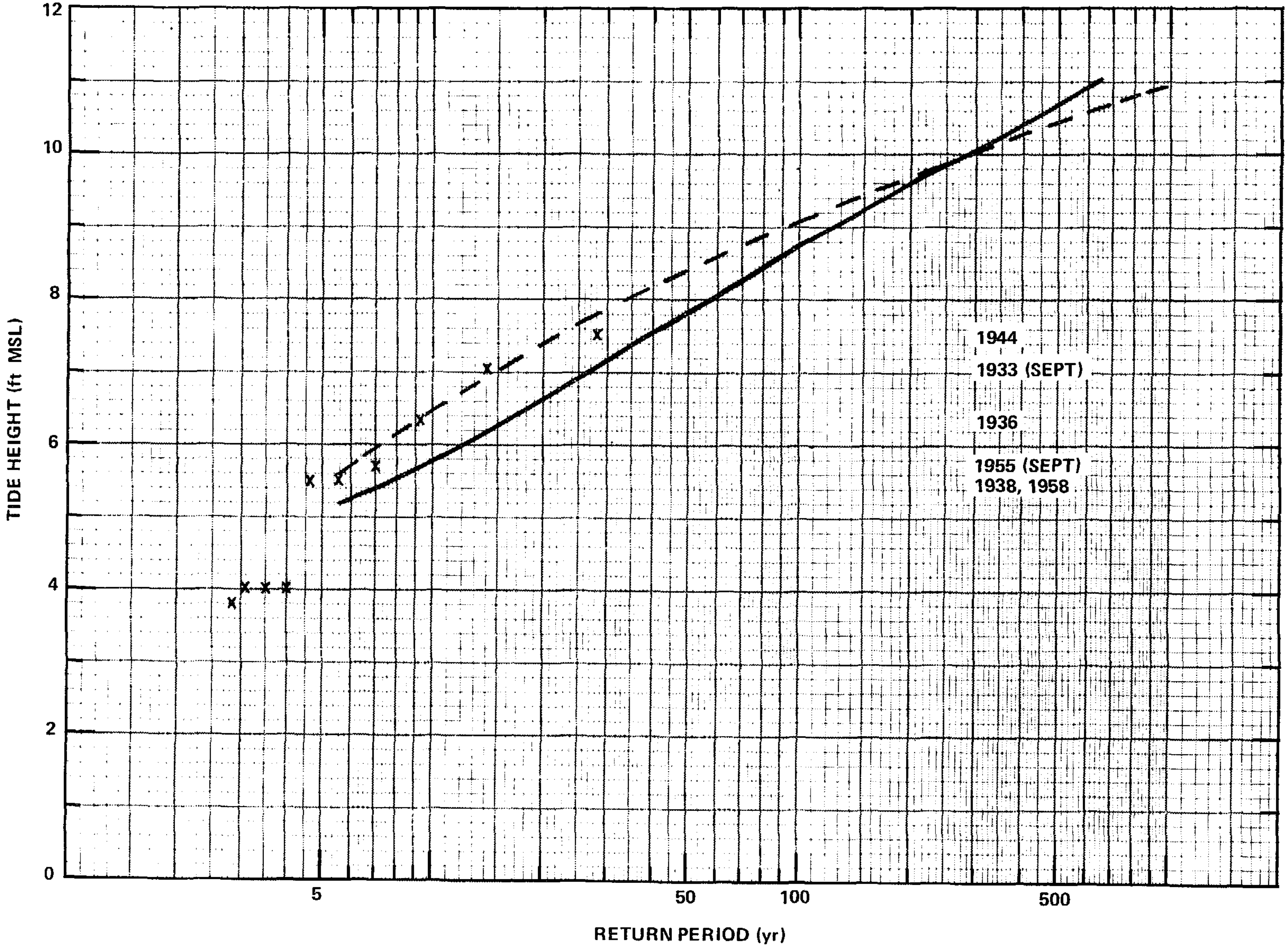

Figure 17.--Comparison of tide frequency curves at Ocracoke Inlet, (——) this report, (-—-) Corps of Engineers report (1963).

(Continued from inside front cover)

NWS HYDRO 15 Time Distribution of Precipitation in 4- to 10-Day Storms--Arkansas-Canadian River Basins. Ralph H. Frederick, June 1973. (COM-73-11169)

NWS HYDRO 16 A Dynamic Model of Stage-Discharge Relations Affected by Changing Discharge. D. L. Fread, December 1973. (COM-74-10818)

NWS HYDRO 17 National Weather Service River Forecast System--Snow Accumulation and Ablation Model. Eric A. Anderson, November 1973. (COM-74-10728)

NWS HYDRO 18 Numerical Properties of Implicit Four-Point Finite Difference Equations of Unsteady Flow. D. L. Fread, March 1974.

NWS HYDRO 19 Storm Tide Frequency Analysis for the Coast of Georgia. Francis P. Ho, September 1974. (COM-74-11746/AS)

NWS HYDRO 20 Storm Tide Frequency for the Gulf Coast of Florida From Cape San Blas to St. Petersburg Beach. Francis P. Ho and Robert J. Tracey, April 1975. (COM-75-10901/AS)

NWS HYDRO 21 Storm Tide Frequency Analysis for the Coast of North Carolina, South of Cape Lookout. Francis P. Ho and Robert J. Tracey, May 1975. (COM-75-11000/AS)

NWS HYDRO 22 Annotated Bibliography of NOAA Publications of Hydrometeorological Interest. John F. Miller, May 1975.

NWS HYDRO 23 Storm Tide Frequency Analysis for the Coast of Puerto Rico. Francis P. Ho, May 1975. (COM-11001/AS)

NWS HYDRO 24 The Flood of April 1974 in Southern Mississippi and Southeastern Louisiana. Edwin H. Chin, August 1975.

NWS HYDRO 25 The Use of a Multizone Hydrologic Model With Distributed Rainfall and Distributed Parameters in the National Weather Service River Forecast System. David J. Morris, August 1975.

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